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Journal
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Vol. 202 NOVEMBER, 1926 No. 5

THE MECHANISM OF THE FATIGUE FAILURE OF METALS.*

BY

H. F. MOORE.

Research Professor of Engineering Materials, University of Illinois; In Charge, Investigation of the Fatigue of Metals.

IN THIS paper it is intended to show a picture—perhaps cartoon would be a more suitable term—of what happens when metal fractures under repeated stress. It should be remembered that all pictures, especially cartoons, are imperfect and omit many details of the thing pictured. A good picture is one which shows correctly and vividly the important features of the thing pictured. Furthermore, any picture must be a view from some definite viewpoint. In considering any picture of the failure of metals under stress at least two viewpoints must be considered: (1) The viewpoint of the engineer and the elastician, and (2) the viewpoint of the metallographist. Possibly a hasty glance may be taken at the subject from the viewpoint of the physicist with his recently developed X-ray spectrograph for determining the arrangement of atoms in materials.

The work of the structural engineer, the machine designer, and the elastician has resulted in the development of a system of mathematical analysis by which it is possible to compute stresses and strains in rods, struts, beams, and shafts. The structural engineer and the machine designer are, for the most part, followers of Rankine, that Scotchman who stands out as the great liaison officer between engineering theory and practice. The

*Presented at a meeting held Thursday, April 8, 1926.

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elasticians are followers of Navier and St. Venant, and they have acquired skill in the use of far more delicate mathematical tolls than those used by the Rankine folk. There is no conflict in principle between the engineers and the elasticians, all of them build their system on the same picture of an ideal material, and all make the following assumptions:

(1) Material is homogeneous, continuous and capable of indefinite division, each successively smaller piece having the same qualities as the original material.

(2) Material may be regarded as isotropic, equally stretchable or compressible in all directions.

(3) Hooke's law (as the stress; so the strain) is true.

This Rankine-St. Venant viewpoint so dominates the field of thought about stresses and strains and strength of materials that it has become an instinctive view. The stress in a tie rod is thought of instinctively as P/A, load divided by area; the extreme fibre stress in an I-beam as Mc/I, bending moment divided by section modulus; the elastician thinks of the localized stress around a small hole in terms of a mathematical formula.

The ordinary (Rankine) formulas for rods, beams, columns, and shafts can be used to determine certain important stresses in machine and structural parts; and these stresses are usually assumed to be the only important ones, such stresses as the flange stress in an I-beam, the outside fibre stress in a shaft, etc. These formulas do not furnish a means for determining the localized stresses which exist by the thousand in all structural and machine parts: The stress at the root of a screw thread (at least four times P/A for a U. S. standard thread), stress around a rivet hole, stress at the root of a key way in a shaft, etc. These localized stresses are ordinarily simply neglected on the assumption that they are incapable of doing much damage to the part as a whole—an assumption which is, in general, true for parts made of ductile metal *under loading repeated only a few times.*

For certain cases of localized stress the more elaborate methods of the general theory of elasticity give solutions; thus the stress at the edge of a small hole in a plate can be computed to be about three times the average stress in the plate near the hole. However, for many cases of localized stress there have yet to be developed methods of solving the complex differential equations involved. For some of these complicated cases, mechanical solu-

tions have been devised, such as the use of transparent specimens viewed by polarized light, and the soap film method of estimating shearing stress in irregularly shaped bodies under torsion. More and more the machine designer and the structural engineer will have to become familiar with the more searching analytical methods of the mathematical theory of elasticity.

The Rankine formulas and the St. Venant formulas have been and are of enormous use, but they are to be *used,* not *worshipped.* The assumptions on which they are founded are not strictly true. Materials, at least all ordinary structural materials, are not homogeneous and cannot be subdivided indefinitely without change of properties. This means that the ordinary formulas of mechanics of materials may be regarded as giving results "statistically" accurate, that is accurate for the general behavior of a group of, say, a few thousand crystalline grains of metal, but not accurate for the behavior of the metal in any one grain. In considering *dead load* strength of machine and structural parts made of *ductile metal,* such a "statistical" view is satisfactory. Unless a considerable mass of metal is deformed beyond the yield point no serious structural damage is done. Around the rivet holes in an I-beam, there may be dozens of minute areas stressed to the yield point and no damage is done to the beam as a whole so long as the load is steady.

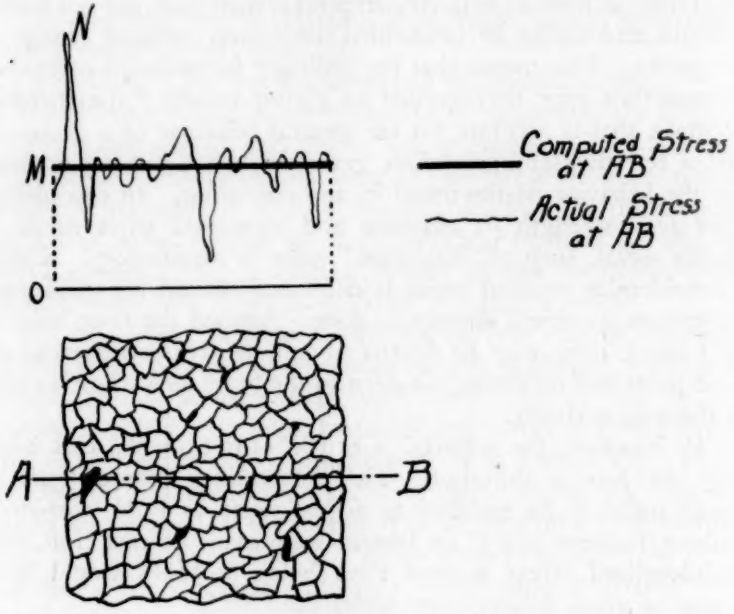
If, however, the material is brittle (for example, cast iron) then the case is different. The outstanding characteristic of brittle metal is its inability to adjust itself to local over-stress without fracture and if an I-beam were made of cast iron, then high-localized stress around rivet holes probably would be a source of grave danger, even under dead load.

The case is still different for repeated loading and under repetitions of loading minute cracks tend to form at points of highly localized stress and to spread, and this is true both for brittle and for ductile metal. The spreading of such a crack, like a minute hack-saw cut, gradually diminishes the area of sound metal remaining in any cross-section of a piece; and the end of a spreading crack is in itself a point of highly localized stress, so that there is a strong tendency for the crack to be self-perpetuating. *Under repeated loading localized stress in a structural or machine part cannot be neglected* even if parts are made of ductile metal.

Taking now the viewpoint of the metallographist, three stages of deformation may be distinguished as metal is subjected to increasing static stress, elastic deformation, slip, and fracture.

Elastic deformation, as the machine designer and the structural engineer see it, consists of a very slight stretching, compressing or sidewise shoving (shearing detrusion) and this slight deformation disappears if the stress is released. It has been noted that the engineer and the elastician think of stress in a metal as a

FIG. 1.

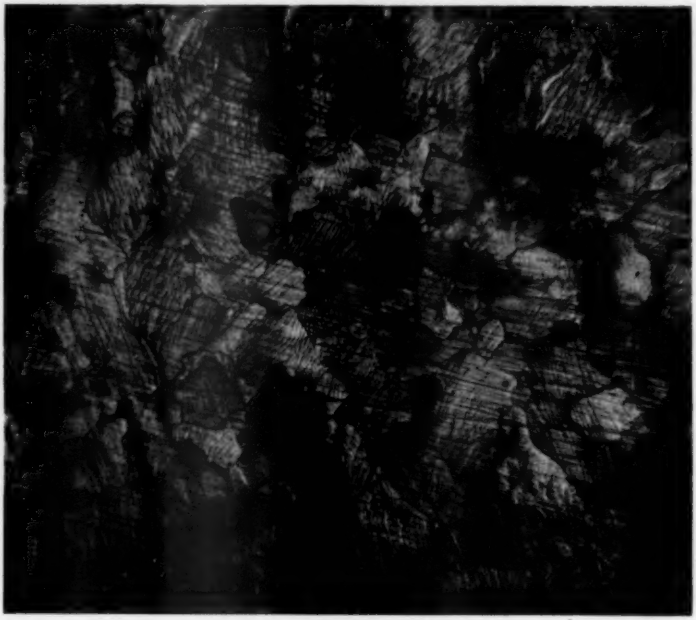


regularly distributed internal force, but if metals be viewed through the metallographist's eyes they are seen to be made up of irregular crystalline grains, and between grains and within grains unfavorably placed there must be many minute areas under very high stress. This is illustrated in a rather crude way in Fig. 1. If in addition to the irregularity of intergranular stresses there is considered the effect of non-metallic " inclusions " and of minute holes which are found in many metals, the possibilities of still higher localized stresses are evident. The stresses computed by the ordinary formulas of mechanics of materials are much lower than the stresses developed over many minute areas

in the metal, perhaps computed stresses are only a small fraction of the actual localized stresses existing in structural and machine parts.

In recent years the X-ray spectroscope has given a picture of the atoms in a crystalline grain of metal, held together by forces whose nature is as yet a mystery, and arranged in some regular geometric pattern with a border region at grain boundaries having

FIG. 2.



Magnification 100 X.

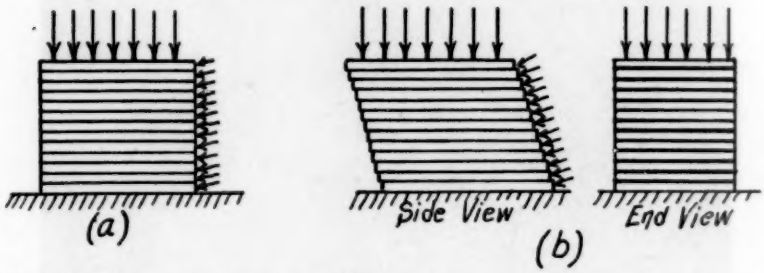
a more or less irregular atomic arrangement. The regular pattern of atoms which is repeated to make up a crystal is known as the space lattice of a metal, and from the viewpoint of the student of atomic structure elastic strain consists of a slight distortion of the space lattice, which distortion disappears when stress is released.

As stress is increased in ductile materials there comes about a state of affairs such that along certain planes of weakness in crystalline grains atomic bonds are broken. The divorced atoms slide over a few thousand other atoms, after which most of them

find new partners and form new bonds with them and the remarkable thing is that the new bonds seem to be stronger than the old, after a brief period of restful adjustment. This action is known as "slip" and is shown under the metallographic microscope by a series of lines across a crystalline grain. Such lines are known as "slip lines" or "slip bands," and their appearance is shown in Fig. 2.

Slip may be pictured as an action analogous to that shown by a pack of cards pressed together, face to back, and subjected to

FIG. 3.



slightly oblique endwise pressure, such an arrangement as that shown in Fig. 3*a*. Under a sufficiently heavy push the pack would take a position like that shown in Fig. 3*b*. The end view of the pack is the end view of a stepped surface, and it is the edgewise view of these steps that shows the slip lines through the microscope. If the cards are slipped repeatedly the faces and the backs would become roughened and would offer increasing resistance to further slip.

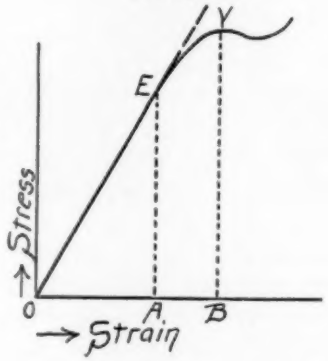
To the metallographist a major significance of slip is the strengthening of planes of weakness within a crystalline grain. If slip could be brought about with no other effects than the exchange and strengthening of atomic bonds it would be an entirely beneficial process so far as strength is concerned. In some cases, *e.g.*, cold-drawn steel, the process is somewhat beneficial to the strength.

However, it is not possible for the process of slip to go on without there being some locations where atomic bonds are broken and new bonds are *not* formed, that is minute, sub-microscopic cracks are developed. The earliest metallographic picture of the mechanism of fatigue failure of metals was a picture of cracks developing at slipping surfaces, growing to visibility under the

microscope, and finally spreading to failure.[1] This is still a fairly satisfactory picture, although two other pictures of the origin and spread of cracks have been recently presented—pictures which do not picture cracks as necessarily originating at slipped surfaces. These pictures will be shown in succeeding paragraphs.

From the viewpoint of the engineering designer slip marks the elastic limit of metal. The commonly used definitions of elastic limit, proportional limit, and yield point are written in stress-strain nomenclature and the terms are not always used carefully. If elastic limit is considered from a metallographic

FIG. 4.



viewpoint, the view may be less foggy. All the various kinds of elastic limits and yield points which are reported from laboratory tests of metals may be regarded as more or less delicate indicators of the beginning of appreciable slip in metal. At low stresses, probably under ordinary working stresses, slip occurs within a very few crystalline grains, but the number of grains so affected is so small that the total slip cannot be detected even by the use of a delicate extensometer. Under somewhat larger stress (*AE*, Fig. 4) slip occurs within a larger number of crystalline grains and on a carefully plotted stress-strain diagram, such as is shown in Fig. 4, a slight deviation from the straight line relation can be detected, or if the load is released, a small permanent set remains. The value of stress for this first detectable irregularity in the stress-strain diagram is reported as proportional limit, or elastic limit. Its precise location depends to a marked

[1] EWING and HUMFREY, "Fracture of Metals under Repeated Alternations of Stress," *Phil. Trans. Roy. Soc.*, A, 200, p. 241 (1903).

degree on the delicacy of instruments used and on the precision of plotting of the diagram. When stress is increased to *BY* (Fig. 4), a general slip takes place throughout the metal under stress, affecting many grains, and stretch can be detected by direct measurement with dividers and a scale—some stretch occurs within the application of any additional stress, and in a testing machine test the beam " drops." This stage marks the yield point of the metal.

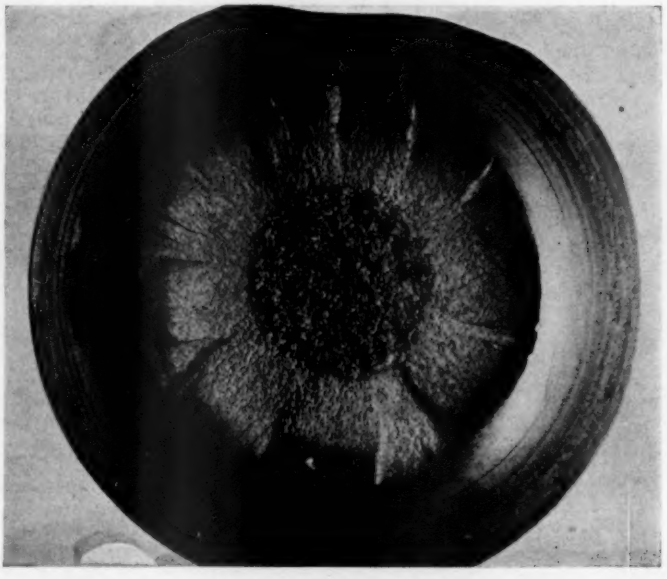
If the strain on a metal is continually increased beyond the original strain where general slip takes place, actual fracture finally occurs. In the case of brittle materials, such fracture occurs before slip becomes widespread enough to show a well-marked yield point. Under a single loading in tension the final fracture of a metal, either a ductile metal or a brittle metal, appears to take place simultaneously over the whole section of a piece of metal, that section seems to act like the famous " one-horse shay " which went to pieces " all at once and nothing first, just as bubbles do when they burst." A careful study of the bursting of bubbles and the failure of tension test-pieces shows that in both cases the actual fracture is progressive, not instantaneous. If the fracture of a tension test-piece be examined, there usually can be found evidence that the failure began at some definite region and spread across the piece, although its spread was rapid. In some ductile metals fracture can be seen to progress across the test specimen. Fracture under a single loading is a very rapid progressive fracture. It may be safely stated that no experimenter has ever loaded a test-piece of metal so carefully and so accurately that all the atomic bonds on a cross-section were broken at the same instant.

Under repeated loading a stress well below the ultimate tensile strength will start a fracture in metal which finally spreads to failure of the entire cross-section of a piece. This spread under repeated loading is very much slower than the spread under a single increasing load. Thousands or even millions of cycles of stress may be required to develop the final failure of a machine part. Not infrequently the spreading crack can be detected before it has progressed to failure and a disaster averted. This repeated stress fracture spreads slowly like a minute hack-saw cut, but its rate of progress is accelerated, and just before fracture, it is almost as rapid as is the spread of fracture under a single increasing load. In fact, a typical fatigue failure usually shows two

distinct zones: (1) A smooth surface where the crack has spread slowly and the walls of the crack are battered smooth by repeated opening and closing, (2) a rough "crystalline" surface indicating the very much more sudden fracture of the core of the piece.

Fig. 5 shows the fracture of a rotating-beam test specimen subjected to cycles of repeated flexure. Fracture started at the outer circumference, and a crack gradually spread inward. The walls of this crack were continually shoved against each other as

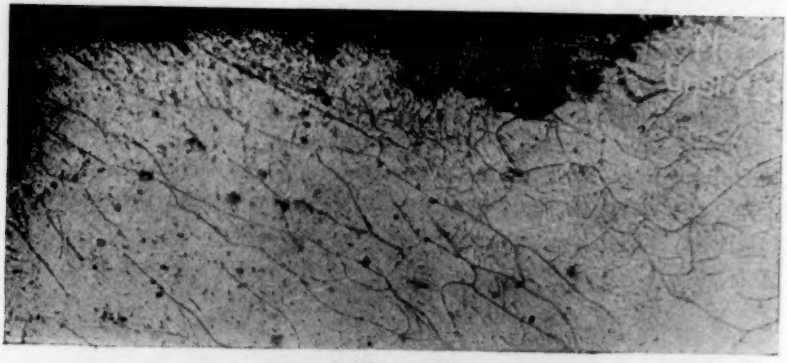
FIG. 5.



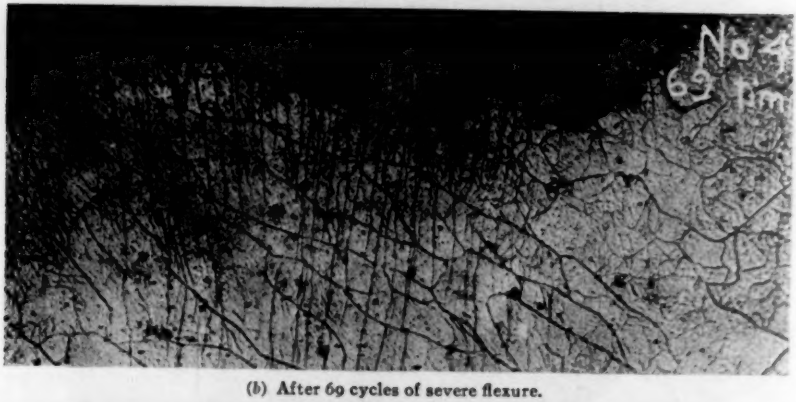
the crack opened and closed under successive cycles of stress. The walls of this part of the crack are worn smooth and occasionally little longitudinal breaks occurred, leaving steps in the surface which roughly resemble ripple marks left on sand by flowing water. When the crack had spread to this inner circle shown in Fig. 5, the failure of the remaining metal progressed so rapidly that a rough "crystalline" surface was left, such a surface as is found when a shaft with a sharp shoulder is fractured under a single very heavy load.

Definite knowledge as to the nature of fatigue cracks in their initial stages is entirely lacking. Attempts to use the microscope to detect fatigue cracks in their very early stages have not met

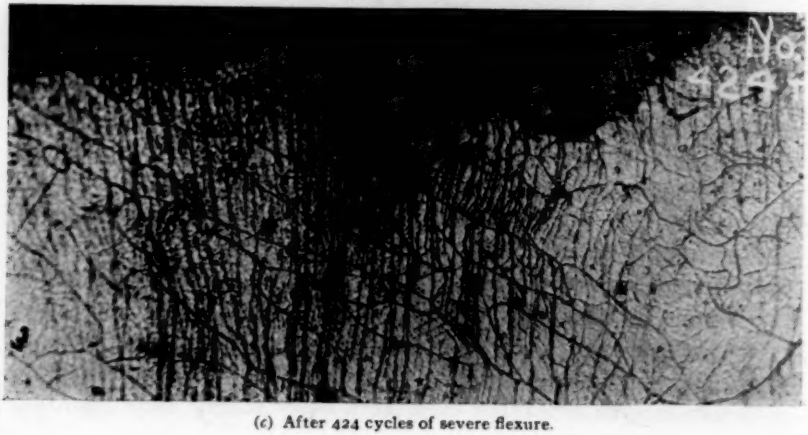
FIG. 6.



(*a*) Unstressed.



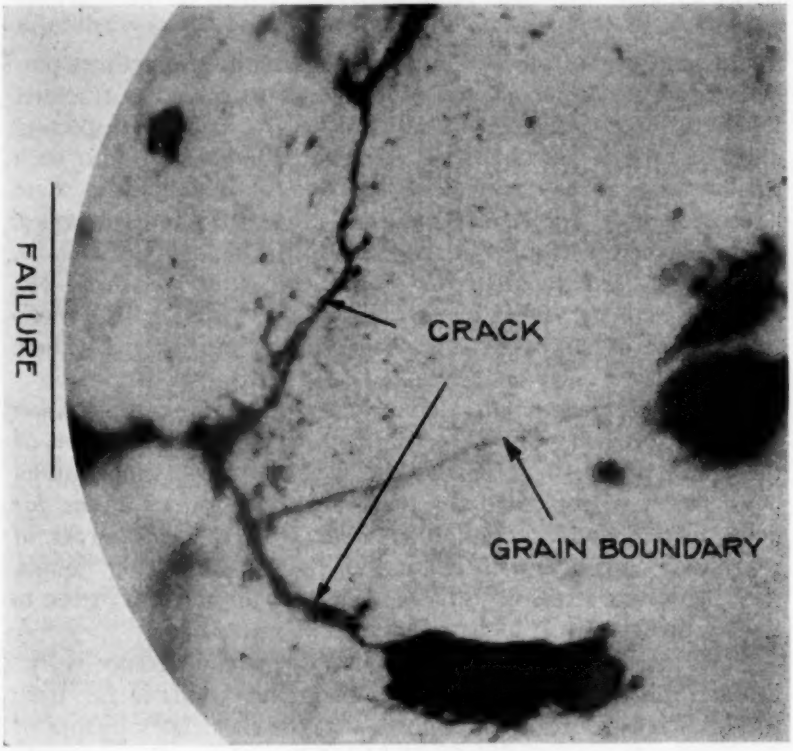
(*b*) After 69 cycles of severe flexure.



(*c*) After 424 cycles of severe flexure.

with much success. If, however, a specimen is notched so as to localize fractures at some definite cross-section, such fatigue cracks in large crystalline grains of metal can be detected quite early in the "life" of the piece, and they can be seen to multiply and to lengthen under successive cycles of stress. Fig. 6 shows

FIG. 7.



Magnification of photograph 3560 times. Micrograph by F. F. Lucas. By permission of the Bell Telephone Laboratories, Inc.

three views of a specimen of armco iron subjected to violent reversals of flexure and the multiplication and lengthening of cracks is evident. It is, however, exceedingly difficult to detect fatigue cracks in small-crystalled metal, and it is exceedingly tedious to hunt for microscopic cracks over any considerable area of surface of metal. Fig. 7 shows a very small fatigue crack in armco iron taken at the magnification of 3560 times. It is to be noted that the crack goes straight across grain boundaries and goes

out of its direct course to take in a non-metallic inclusion. In spite of its difficulties the microscopic study of fatigue cracks in metals offers a very promising field for the investigator. The question of initial stress in metals and of whether such regions of stress are sources of fatigue cracks also needs investigation. Some locations where there are no cracks may be under high internal stress—stress so high that but little additional stress is necessary to start a crack.

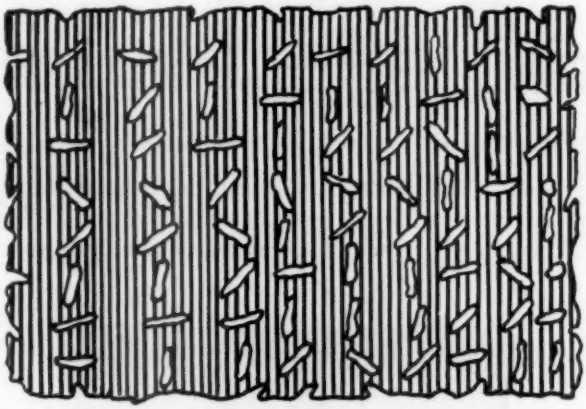
In structural members and machine parts, it is sometimes possible to detect fatigue cracks before they have spread to fracture. Some railroads and street railways make a practice of inspecting axles of cars and locomotives at regular intervals to see if such small cracks can be detected. When this is carefully done there have been very few disasters due to fatigue fractures in axles. In some experiments now in progress at the University of Illinois, it has been found possible to detect cracks in specimens 1⅛ inches in diameter, when about one-half the "life" of the specimen has passed, unless the applied stress is very high. These specimens were cut from car axles.

The whole question of fracture in metals brings up the relation of theoretical cohesion and strength. From a determination of the latent heat of fusion and the latent heat of vaporization, physicists have computed the theoretical cohesion of atoms for many metals, and if cohesion in solids is of the same order of magnitude as cohesion in melting solids and vaporizing liquids, then the tensile strength of most metals should be from fifteen to twenty times as great as it is found to be in tests.

The most obvious explanation of this great difference is that in our ordinary metals the system of atomic bonds is far from perfect. It has already been noted that the elastician's picture of continuous, homogeneous material is not true for ordinary metals. If we look at metals from the viewpoint of the metallographist, we might draw a rough picture of metals by considering them as continuous but not homogeneous. If we think of imperfect bonds between atoms, minute cracks, severe internal stresses which when slightly increased will produce cracks, we may draw a picture from the engineer's viewpoint of metal which is homogeneous but not continuous. Neither of these pictures can claim to be complete. The metallographist's picture does not lend itself to mathematical computations of strength. The engineer's

picture of metal, which may be regarded as homogeneous but which has in it many small holes or many irregularities of outline, *does* lend itself to such computation. The mathematical theory of elasticity and the mechanical means which can be used to solve some of its more complex equations can be employed to determine approximately the effect of these supposed discontinuities. With this apologia for using a method of analysis which is admittedly based on an incomplete picture, but which is believed

FIG. 8.



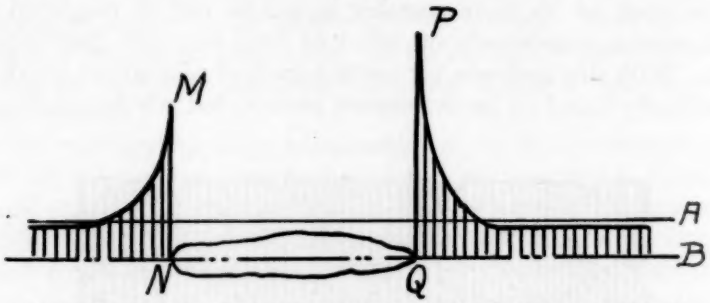
to be useful, the writer would like to develop in some detail a picture of the behavior of metal under stress.

In developing this picture, the writer is following outlines given by two physicists, one the British physicist, A. A. Griffith [2] and the other the Russian physicist, Joffé. These two men present pictures which are not contradictions, but they do emphasize two different sources of irregularity. In Griffith's picture the possibility of minute discontinuities throughout the metal are emphasized. Fig. 8 is a cartoon of the Griffith idea. Metal is pictured as having in it a multitude of minute cracks, cracks say, 0.0002 inch long and a few hundred atoms wide. Such cracks could not be detected by any present-day microscope. If such cracks exist, they must be very numerous and must be scattered throughout the metal, else the metal could not be produced with such dependable physical properties as is found to be the case.

[2] "Phenomena of Rupture and Flow in Solids," *Phil. Trans. Roy. Soc.*, A, 221, p. 163 (1920).

These minute cracks weaken the metal in two ways: (1) By diminishing the area of the cross-section, and (2) by causing very high localized stress at the ends of the crack. Again attention

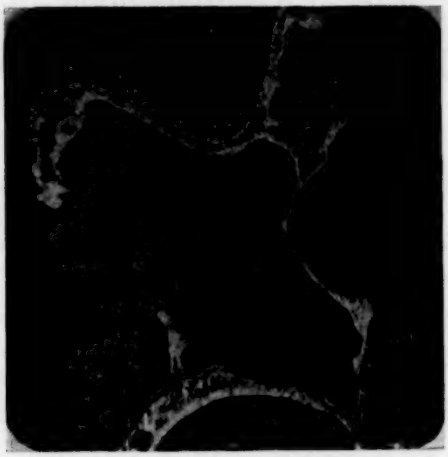
FIG. 9.



AB, mean stress in region near crack. *MN-PQ*, localized stress at ends of crack.

must be called to the limitations of the theory of elasticity and to the improbability that these formulas would apply with any high degree of accuracy to such small areas of metal as are involved

FIG. 10.

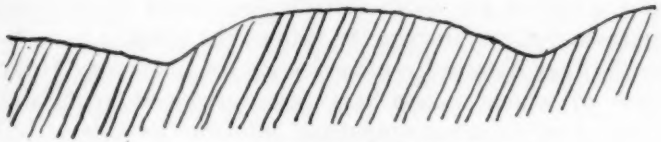


Crack in ferrite-pearlite steel. The crack was filled with a deposit of copper before the piece was polished and hence appears light colored. Note how the crack skirts the strong pearlite grains, and the rounded ends of the crack. Magnification about 350 times. Micrograph furnished by H. A. Schwartz of the National Malleable and Steel Castings Company.

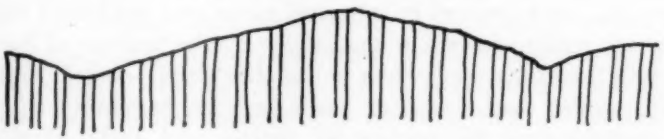
in considering these cracks; however, the general qualitative conclusions of the theory of elasticity may be expected to furnish a useful guide for estimating the general effect of such cracks.

From such general conclusions it would seem that if Fig. 9 represents such a small crack the stress intensification at the ends is a function of the direction of the long axis of the crack with respect to the direction of the stress and a function of the sharpness of curvature at the end of the crack. The reader is reminded

FIG. 11.



0.13 per cent. carbon steel—tool marks.



Tool steel—tool marks.

0.33 per cent. carbon steel—ground finish.

Tool steel—ground finish.

0.33 per cent. carbon steel—reamer finish.

Magnification 360 times. Traced from micrographs of gelatin casts obtained by W. Norman Thomas; see Reports and Memoranda No. 860 of the British Aeronautical Research Committee. By permission of the Controller of his Britannic Majesty's Stationery Office.

that all cracks have rounded ends, and is referred to Fig. 10 for an illustration of this.

The picture given by Joffé emphasizes the irregularities at the surface of the metal as a source of highly localized stress. All metallic surfaces have minute hills and hollows which are, however, large when compared with atomic dimensions, and these

hills and hollows are the sources of stress intensifications, just as are the internal cracks pictured by Griffith. Fig. 11, which shows actual surface irregularities magnified three hundred and sixty times, may be used as the Joffé picture. Evidently there will be stress concentration at the bottom of the minute notches in the surface of the metal and the magnitude of that stress concentration at the root of any notch depends upon depth of the notch and the sharpness of curvature at the root of the notch.

Griffith has obtained some evidence for his theory from tests of glass in which cracks have been produced artificially and also from tests of glass drawn out into fine threads. Joffé has obtained some evidence for his picture from tests of a single crystal of a salt ground to spherical shape and subjected without failure to extreme stress at the middle by the process of immersing it in liquid air and, when it has thoroughly cooled, plunging it into molten lead. Griffith has noted the possibility of stress concentrations at the surface of metals and Joffé admits the possibility of stress concentration between crystalline grains of metal. As noted above, the two pictures are supplementary and not contradictory.

As noted in a previous paragraph, there was an earlier picture of the mechanism of fatigue failure in which cracks were shown as having their origin in planes of slip. This picture is not contradictory to the internal flaw picture given above. Whether the cracks develop after slip or are always present in metal once present, the phenomena of stress intensification and of spread may be imagined as proceeding, as shown in the internal flaw picture.

The writer will attempt to draw a picture of fracture under steadily increasing static load, making it the combination of the internal flaw picture and the surface irregularity picture. In Fig. 12 the left-hand part of the figure refers to the internal flaw picture, while the right-hand represents the surface irregularity picture. Again, the reader is reminded that cracks and notches have roughly rounded ends. (Fig. 10.) Under increasing load at least three things happen: (1) The hole, shown at *a*, and the notch, shown at *b*, spread to the condition shown at *a'* and *b'*, respectively; (2) the curvature of the ends of the crack and the curvature at the bottom of the notch become less sharp, causing diminution of stress concentration and benefit to the metal; (3) slip, as well as fracture, occurs at the ends of the crack and at

the bottom of the notch, probably causing diminution of internal stress, and tending to increase the strength of the material. Under a moderate increase of loading, equilibrium is reached and the damage caused by the crack (or the notch) spreading slightly, causing a reduced cross-section, is balanced by the diminished stress concentration at the ends of the crack or the notch, and furthermore by the tendency to strengthen the material at the points of highest stress. Under a sufficiently great increase of load the spread of the defects overbalances the beneficial effects of lowered stress concentration and failure occurs, and its final progress is very rapid. If the metal has low ductility the strengthening effect and the reduction of internal stress due to slip is slight, since brittle material slips very little before fracture.

To make this picture fit the case of repeated stress a third part must be added. If a load is applied not sufficient to cause failure and that load is then released, the resulting state of affairs may be pictured as at a'' and b''. The crack a'' is longer than the initial crack a and the notch b'' is deeper than the initial notch b. However, the curvature at the end of the crack and at the bottom of the notch may be either sharper or less sharp than at first, that is, stress concentration may be either increased or diminished, and the damage done by succeeding loads may be either greater or less than that done by the first load, depending on the magnitude of the load and upon the nature of the material. It is then not difficult to picture how the repetition of a load smaller than that required to fracture the material at one application may fracture it under repeated applications.

If the load is not merely repeated but is *reversed,* the state of affairs may be pictured as at a''' and b'''. The reversed load might shorten the crack and the notch, although this is by no means certain. It would undoubtedly tend to make the curvature at the ends of the defects more sharp than that after release of load (a'' and b'') and thus to tend to increase stress concentration for the succeeding cycles of stress. It is then easy to see in a general way how cycles of *reversed* stress are more likely to spread a crack to failure than are cycles of *one-direction* stress at the same maximum value.

To the user of material, the significance of slip seems to lie in the location of some elastic limit or yield point which marks the practical limit of retention of original form by a machine part

or a structural member. The significance of spreading fracture lies in the location of an endurance limit or fatigue limit, below which repetition or reversal of loading will not cause a crack to spread to failure. Both limits are most conveniently measured in terms of computed stress, that is, stress computed by the ordinary formulas of mechanics of materials, which, as has been pointed out, is really an average stress for a considerable number of crystalline grains of metal.

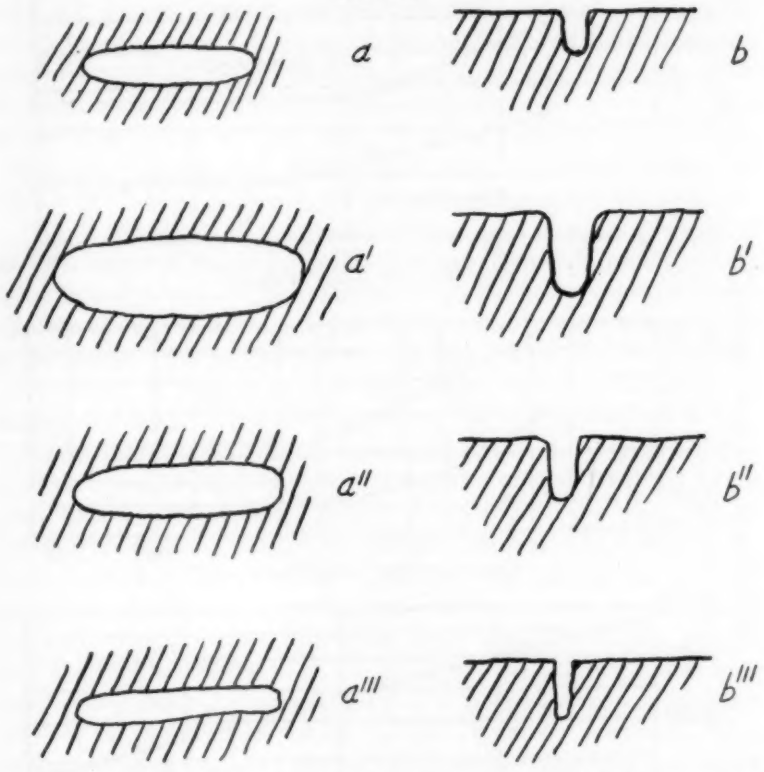
The elastic limit or yield point cannot be determined readily from microphotographs, and the determination is usually made from the data of an actual mechanical test of the material. The most accurate determination of these limits is made from a diagram drawn with stress as ordinates and strains as abscissa—the ordinary stress-strain diagram. The endurance limit or fatigue limit is most readily determined by actual tests of specimens to destruction under repeated stress. The determination can be most conveniently made from a diagram in which computed stress (S) is plotted as ordinates and number of cycles of stress required to cause fracture (N) is plotted as abscissa. Such diagrams are called stress-cycle diagrams or S-N diagrams. The endurance limit is determined when this S-N diagram becomes horizontal. Methods of making endurance tests have been described so frequently that it is not necessary to give their detail here.[3] It is usually convenient to plot the values of numbers of repetitions of stress required to cause fracture to a logarithmic scale, and in some laboratories stress is also plotted to logarithmic scale. Fig. 13 shows typical S-N diagrams. The plotted points marked with arrows indicate specimens not broken.

From an examination of many of these S-N diagrams the writer finds that, in general, they approach a horizontal direction as the number of cycles of stress is increased. The S-N diagrams obtained from various metals extend to as high as a thousand million cycles of stress and seem to give good evidence that endurance or "life" of metal will be indefinite if the computed stress is less than that for which the curve for a metal becomes horizontal. The S-N diagram for hot-rolled monel metal shown

[3] See Bulletins 124, 136, 142, 152, Eng. Expt. Sta. Univ. of Ill. R. R. MOORE, *Proc. A. S. T. M.*, 23, Part II, p. 106 (1923). D. J. MCADAM, JR., "Endurance of Steel under Repeated Stress," *Chem. and Metal. Eng'g*, Dec. 14, 1921.

in Fig. 12 is of a rather unusual type. It seems to represent an extreme case of slow development of endurance limit (no endurance limit developed at 800 million cycles of stress). It should be noted that Doctor McAdam, of the Naval Engineering Experiment Station at Annapolis, has obtained an *S-N* diagram for

FIG. 12.



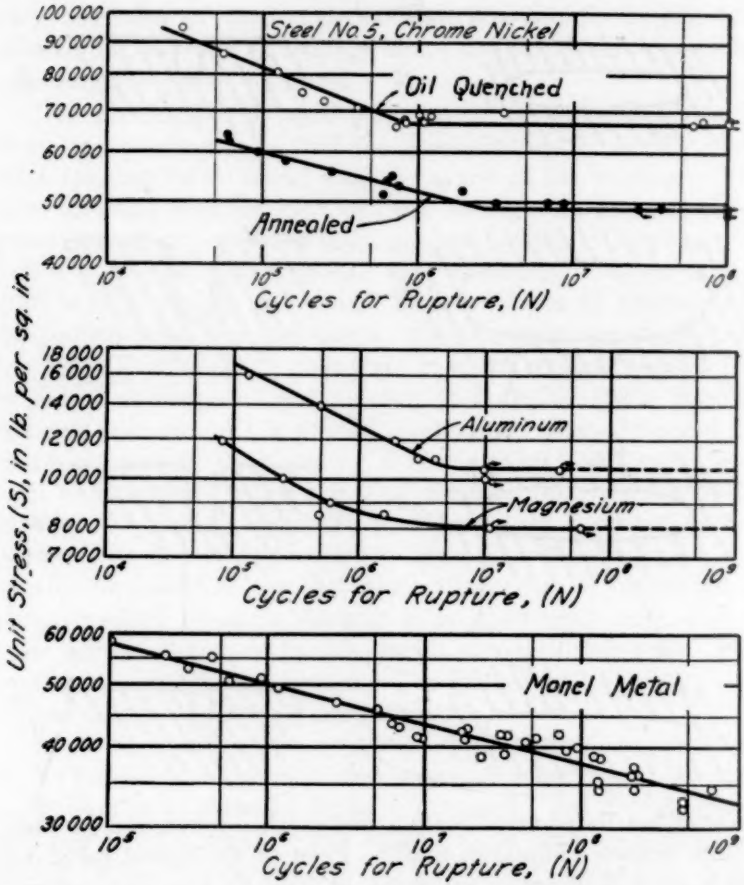
annealed hot-rolled monel with a well-marked horizontal part and a quite definite endurance limit.[4] Perhaps the monel metal for which an *S-N* diagram is shown in Fig. 12 had high internal stresses and under light applied loads cracks start, but spread with extreme slowness.

Returning to the pictures of cracks and notches spreading to failure: Below the endurance limit, the beneficial effects of metal

[4] Such a diagram for *annealed* monel has very recently been obtained at Illinois.

improved by cold working, and of diminished stress concentration may be pictured as overbalancing the injurious effect of spreading cracks. Above the endurance limit the destructive effect predominates. In this connection it should be noted that evidence that

FIG. 13.



material may be improved by repetition of stress below the endurance limit has been obtained both in England and in this country. Specimens stressed to some millions of repetitions of stress a little below the endurance limit were found to develop a new endurance limit higher than that for the virgin metal—20 per cent. higher in some cases.

The correlation of endurance limit with other physical properties is of interest. For the metals tested there seems to be no direct correlation between endurance limit and ductility, or between endurance limit and impact value. There seems to be a rather poor correlation between endurance limit and elastic limit. There seems to be a well-marked correlation between endurance limit and tensile strength—and incidentally Brinnel, scleroscope, or Rockwell number. This result fits in fairly well with the picture presented of fatigue failure as a spreading *fracture*. For wrought ferrous metals the endurance limit under reversed stress varies from 40 to 60 per cent. of the ultimate strength. For non-ferrous metals this "endurance ratio" (a term coined by Doctor McAdam) is lower, ranging from 25 to 45 per cent.

While ductility and fatigue strength are not directly correlated, yet ductility is a desirable quality for metals which have to withstand repeated stress. In laboratory fatigue tests, specimens are subjected to cycles of stress, and the range of stress for each cycle is the same. In service, most machine parts are occasionally subjected to a few cycles of high stress but are subjected to millions of cycles of working stress. Now suppose these few cycles of high stress start a crack and cause it to spread for a short distance. Will subsequent cycles of a normal working stress cause this crack to spread, once it is started by the high stress? The answer to this question has not yet been completely obtained. Tests now in progress at the University of Illinois on car-axle steel have shown that once a crack starts it may spread under cycles of stress at least 35 per cent. lower than the original endurance limit of the metal. It seems highly probable that the tendency for a crack to spread, once it is started, depends in some measure on the ductility of the metal. Tests on specimens with sharp notches or holes which artificially cause high localized stress indicate in a general way that such artificial defects do more damage in the case of brittle materials than in the case of ductile materials, although test results show that there are evidently other factors concerned as well as ductility. Ductility in metals then may be looked on as furnishing some protection against destructive damage by occasional over-stress, although it is not a direct factor in increasing fatigue strength of metal.

The question may be asked, "What can be done to prevent fatigue failure of metals?" The visionary student of metals—

and may we always have some visionary students—will fix his eye on the goal of producing metals having the strength which the physicist says perfect metals should have, say on producing steel with an endurance limit of a million pounds per square inch. This visionary student has a hard path to attain his ideal. Metal when it solidifies from its liquid state does not naturally settle into an unstressed network of perfect atomic bonds and even if this could be brought about the surface of the metal is not perfect, but, even when polished, is covered with hills many hundreds of atoms high and valleys many hundred atoms deep. Even if a perfect surface were obtained, it would soon be roughened by wear and atmospheric corrosion. But even if the achievement of this ideal goal seems impossible, a good deal can be done at once to improve fatigue strength of metal. Dirty metal can be avoided, recognizing that every little inclusion is what Doctor Gillett, of the Bureau of Standards, calls a "stress raiser." Machine designers can avoid putting artificial "stress raisers" into their designs. They can avoid sharp shoulders, notches, screw threads under repeated stress, deep sharp-cornered key ways under torsion, holes bored in regions of high general stress; and if they do this great improvement can be brought about in the fatigue strength of machine and structural parts.

To sum up: In considering the fatigue of metals under repeated stress, it becomes necessary to recognize that the ordinary formulas for stress and strain are strictly true only for an ideal metal, homogeneous and without any discontinuities (flaws) in it.

Actual metals are not ideal in this respect and hence for them the ordinary formulas for stress and strain have a high degree of precision only if a large number of crystalline grains are considered together.

Actual metals do not develop strengths under load so great as would be expected from the computed "cohesion" of their atoms. Under repeated stress their strength is still smaller, and under reversals of stress the strength of metals is even lower than under repetitions of stress not involving reversal.

These various differences in strength may be at least partly explained by considering the intensification of stress which occurs at the root of a surface scratch or notch and at the end of a minute crack in the metal.

THE CRACKING OF PETROLEUM.*

BY

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THE volume of literature relating to the cracking of petroleum is enormous and ever increasing. Presentation of this paper requires, therefore, no small amount of audacity, especially as no attempt will be made to contribute any information new to those familiar with the art. The author's sole justification is a belief that a rapid review of the subject may prove of some interest to those outside the petroleum industry.

Petroleum is a term often used, in a broad sense, to designate not only crude petroleum but also the products derived therefrom. Crude petroleum may be defined [1] as: "A naturally occurring mixture consisting predominantly of hydrocarbons, or of sulphur, nitrogen or oxygen derivatives of hydrocarbons, which is removed from the earth in liquid state, or is capable of being so removed." Crude petroleums show extreme variations in properties, both physical and chemical. These differences are reflected to a considerable degree in the products obtained from the crude and the differences are both qualitative and quantitative. Nevertheless all crude petroleums are initially refined by a distillation process conducted under conditions adapted to the particular crude handled. Such primary distillation results, broadly speaking, in the separation of the crude petroleum into three products; first, a mixture of gases which are not condensed; second, a series of liquid or semi-liquid distillates, and third, a residuum left in the still.

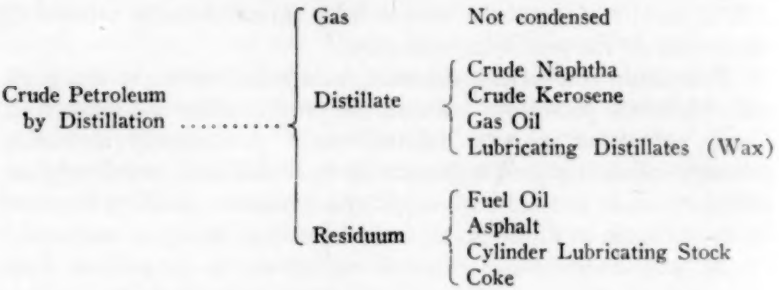
The usual major products of the primary distillation are shown in the chart on the following page.

The quantity and quality of the products named depends, first, upon the nature of the crude petroleum and, second, upon the method of distillation. Two factors are of prime importance in the primary distillation of crude petroleum, namely, the distillation temperature and the duration of exposure to such tempera-

* Presented at a meeting held Thursday, March 25, 1926.

[1] *Proc. A.S.T.M.*, 25, Part 1, p. 287 (1925).

ture. Petroleum is distinctly sensitive to chemical change under the influence of high temperature, for example 600° F. For this reason high boiling-point petroleum products, such as lubricating oils and asphalts, are prepared by distillation in a current of commingled steam or other inert gas or sometimes *in vacuo*. These means permit transformation from the liquid to the gaseous state at temperatures very much below the boiling-point of the mixture at atmospheric pressure. Such form of distillation is known as a "non-cracking" distillation. Pennsylvania crude petroleum when subjected to careful, non-cracking distillation, yields, as residuum, cylinder lubricating stocks of excellent quality. Mexican crude under the same conditions yields, as residuum,



excellent asphalt. If, however, either Pennsylvania or Mexican crudes are distilled without the use of steam or vacuum or the equivalent, the residuum obtained is petroleum coke. Coke is not a constituent of crude petroleum, but is formed by a chemical change during the exposure to high temperature. Such coke formation is attended by the evolution of appreciable quantities of fixed gas and of low-boiling distillates. It is to the production of chemical changes of this sort that the term "cracking" is applied in the petroleum industry. In other words, cracking is a chemical decomposition of petroleum usually associated with high-temperature treatment.

Cracking of petroleum was first utilized commercially about 1862 for the purpose of increasing the yield of kerosene obtainable from crude petroleum by distillation. Partial condensation of the vapors and return of the condensate to the still permitted maintenance of high distillation temperatures for a longer time and resulted in the formation of appreciably larger quantities of kerosene, due to decomposition or "cracking" of hydrocarbons

of boiling-point distinctly higher than that of kerosene. In those days, kerosene was the desired product and maximum yields of this material were therefore required.

Another important commercial utilization of cracking was in the manufacture of illuminating gas, by the Pintsch process and others. Gas manufacture continues to utilize cracking in a highly destructive distillation process where gas oils and even residuums are converted into fixed gases. The tendency of petroleum hydrocarbons to crack when exposed to high temperatures is also commercially important for altering the nature of wax-bearing distillates so that the paraffine wax may be separated from the liquid oil by filter pressing. The effect of cracking is to produce crystalline paraffine from the amorphous forms which appear to exist in the crude. Yet another application of the cracking tendency of hydrocarbons has been in increasing the fluidity of extremely viscous residual fuel oils. By this means, semi-solid fuels, such as the residuum from heavy gravity Mexican crude, have been rendered sufficiently fluid to feed satisfactorily to the usual industrial fuel-burning systems.

All other beneficial results obtained by the cracking of petroleum fade into insignificance when compared with the production, by this means, of the motor fuel which we call gasoline. Consequently, " cracking " is popularly understood to mean the chemical conversion of relatively high boiling-point hydrocarbons into gasoline of decidedly lower boiling-point range.

The importance of gasoline in the economic life of to-day needs no extended discussion. Prior to the advent of the automobile, gasoline found considerable use as fuel for cook stoves, as cleaning fluid and solvent and for street lighting. The automobile, however, created a demand which rendered increased gasoline production imperative and at a rate of increase which is truly remarkable and worthy of some emphasis. Some thirty years ago the automobiles of this country were to be found in a circus or similar exhibition. In 1900 the number of automotive engines in the United States was around 10,000; in 1910 about 500,000; in 1920 about 9,000,000 and in 1925 about 20,000,000. Incidentally the forecasted number for 1950, is 45,000,000, including aeroplanes.[2]

Cracking petroleum to make gasoline commercially is only

[2] *Am. Pet. Supply and Demand*, p. 198.

thirteen years old, dating back to the operation of the first Burton pressure stills at Whiting, Ind., in 1913. The fascinating story of the development of the early process is available in the modest words of Dr. William M. Burton himself, on various occasions when he has been publicly honored by such scientific bodies as the American Chemical Society [3] and the Society of Chemical Industry.[4] His remarks make most interesting reading for any scientist and are distinctly illuminating as to the difficulties encountered and overcome.

The original Burton cracking process [5] consisted of distilling a high-boiling petroleum distillate, such as gas oil, under pressures of 80 to 100 lb. per square inch. Under such pressure, gas oil, normally starting to boil at 500° F., could be heated in liquid form to 700° F. and higher. At this temperature substantial cracking occurred and there resulted a pressure distillate containing gasoline boiling below 400° F. Commercial cracking to produce gasoline is therefore a deep-seated chemical transformation and it was accomplished under the leadership of distinguished industrial chemists.

Nevertheless, the chemistry of this transformation was not and is not clearly understood. This statement is made with full cognizance of chemical reaction equations to be found in many text-books. Such equations fail to represent what actually happens and no simple equation can ever succeed in this respect, since the chemistry of cracking is necessarily complicated by many factors. In the first place, petroleum products are extremely complex mixtures, not only of many hydrocarbons but of many classes of hydrocarbons, together with their sulphur, nitrogen and oxygen derivatives. It is, therefore, quite impossible to represent any commercial petroleum product by a chemical formula. In the second place, the various chemical classes of hydrocarbons contained in petroleum behave differently under the same conditions as to high temperature and time of exposure. In addition to this, different individual hydrocarbons of the same chemical class also behave differently under the same conditions. In the third place, the isolation of pure chemical individuals from the heterogeneous mixture known as petroleum is decidedly difficult and thus the

[3] *Jour. Ind. and Eng. Chem.*, **10**, 484 (1918).
[4] *Jour. Ind. and Eng. Chem.*, **14**, 162 (1922).
[5] U. S. Patent 1,049,667, Jan. 7, 1913.

preparation of raw materials for scientific research upon cracking requires knowledge and skill and patience to the last degree. The subject is being investigated intensively both in the United States and abroad and the sum total of scientific knowledge is being slowly augmented. Collaboration and check testing of each research may enable the chemists of our grand-children's generation to understand the chemistry of cracking and to control it with assurance of results. At present, however, the situation appears to be well described by the words of two British writers who state:[6] "Very little is known about the chemical composition of the initial charging stocks which are used in cracking; and about as much is known of the final products, while the intermediate reactions are only guessed at."

Avoiding the guessing field, the present paper will confine itself to the known facts, namely, that cracking produces, first, non-condensed gas containing methane, hydrogen, ethane, ethylene and other compounds; second, a condensable liquid, gasoline, whose boiling-point range is about 300° F. below that of the raw cracking stock; third, liquids and solids of boiling-point higher than that of the cracking stock, and last but not least from an operating standpoint, a non-volatile solid mixture termed carbon or coke.

The fact remains that cracking petroleum is an art rather than a science. Furthermore, it is largely a mechanic art, owing very little to petroleum chemistry directly, and this in spite of the fact that commercial cracking found its origin in the vision and courage of a group of chemists. The actual achievements in the cracking art have been due in no small degree to mechanical engineering knowledge, skill and ingenuity. Therefore, present cracking operations, as far as present knowledge goes, are largely dependent on engineering considerations.

It is customary to classify cracking process for the manufacture of gasoline as:

(1) Vapor phase processes wherein vapors of petroleum hydrocarbons are subjected to heat treatment.

(2) Liquid phase processes where at least the major portion of the treated oil is in liquid form.

(3) Catalytic processes in which the cracking reaction is accelerated by the use of various substances.

[6] PITKETHLY and DUNSTAN, *Jour. Inst. Pet. Tech.*, **2**, p. 363 (1925).

Vapor phase processes have found but little commercial use and most of them have been abandoned. One reason has been the difficulty of refining gasoline made by vapor phase cracking to meet conventional ideas as to quality. With changing standards in this respect, and with increased attention being paid to the actual merits of cracked gasoline as a motor fuel, it is not improbable that vapor phase cracking will become increasingly important.

Catalytic processes have been used to only a slight extent and with many of them at least there is reasonable doubt as to how much of the cracking effect is actually due to the catalyst. The use of aluminum chloride is unquestionably effective in producing gasoline of good quality and in good quantity. With cheapened cost of aluminum chloride and better methods of recovery, this method of cracking is also likely to be important.

The bulk of commercial cracking is at present accomplished by the so-called liquid phase processes which are, therefore, of greatest immediate importance. In a paper delivered before the American Institute of Mining and Metallurgical Engineers last month, the following statement is made by an engineer,[7] who has made a painstaking survey: "At the present time, there are twenty-six cracking systems in commercial operation; each regularly running 100 or more barrels of charging stock per day. There are also twenty-eight commercial-size experimental or demonstration systems in occasional operation." It is obviously not expedient to attempt a description of all of these processes. Therefore, only those which are now being used extensively and increasingly will be considered here.

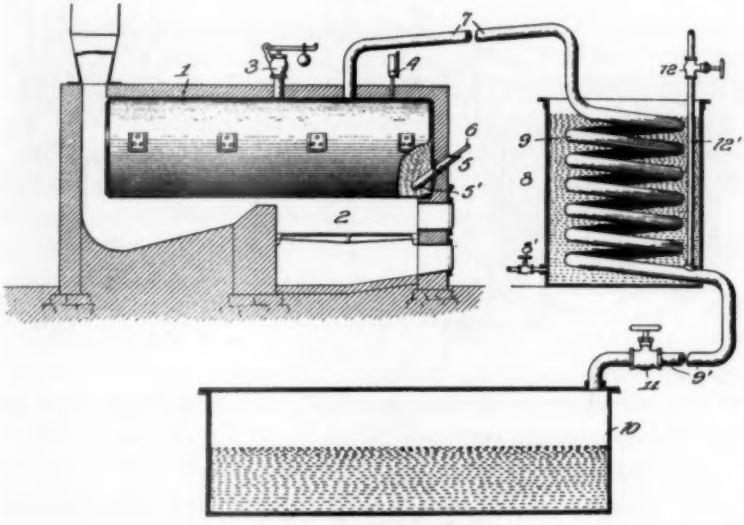
The Burton process was first carried out in the form of apparatus shown in Fig. 1. The still (1) was a horizontal cylinder, 8 feet in diameter, 20 feet long, with a charging capacity of 8000 gallons. It was made of ½-inch mild steel plate, riveted construction. The other essential parts of the apparatus were the furnace (2); safety valve (3); pressure gauge (4); thermometer well (5); a long vapor line slanting toward the still (7); condensing coil (9); pressure relief lines for gas (12) and for liquid (11); also a draw-off line for residuum in the still at the end of the run.

Operation of this apparatus was about as follows: Gas oil used

[7] CHARLES L. PARMELEE, *Nat. Pet. News*, Feb. 24, 1926.

as charging stock was a petroleum distillate boiling over a range of approximately 500° F. to 700° F. A 200-barrel charge of oil was heated to about 675° F. with resulting cracking and generation of pressure. This pressure was maintained at 80 to 100 lb. per square inch, any excess pressure being relieved. With the entire apparatus, including the condenser, under this pressure, distillation was carried on slowly, taking off about 2 per cent. of the charge per hour until about 60 per cent. "pressure distil-

FIG. 1.



Burton cracking still (1913).

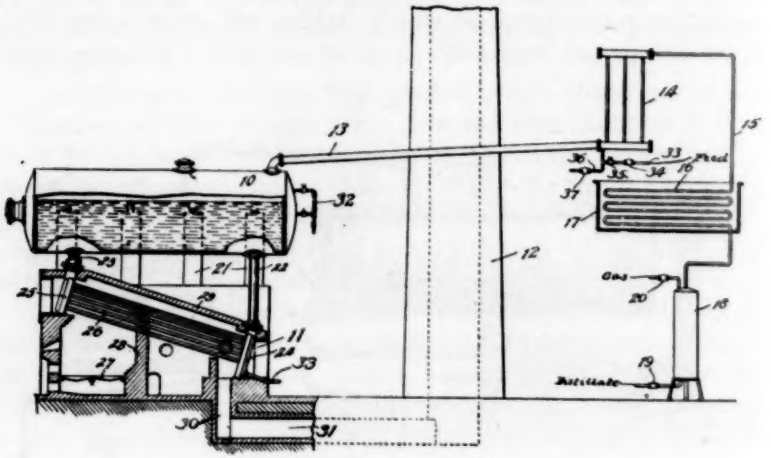
late" was obtained. At this point the temperature of the residuum was about 800° F. and distillation was discontinued. The "pressure distillate" contained gasoline equivalent to about 30 per cent. of the original gas oil charge, this gasoline being separated and refined by the usual methods. The residuum represented about 40 per cent. of the charge and contained coke equivalent to, perhaps, 5 per cent. of the charge.

The formation of coke has been the most difficult obstacle to satisfactory cracking by any process. Its undesirability in the Burton shell still is obvious, inasmuch as carbon settling on the bottom of the still resulted in "hot spots" due to overheating. Such "hot spots" on a pressure still forced very prompt shut

down. This condition was later ameliorated appreciably by much use of a false bottom on which the coke was deposited.

Various operating difficulties led to the use of a tubular still similar to a Heine boiler. This is known as the Burton-Clark [8] and is shown in Fig. 2.

FIG. 2.



Burton-Clark still.

The mechanical advantages of this arrangement over the original Burton still were:

(1) Greater heating surface.

(2) Greater rate of heat transfer due to high liquid velocity through the tubes.

(3) Tendency of carbon to settle in the still not directly heated rather than in the tubes which were exposed to the fire.

(4) Greater safety.

Various other modifications and improvements of the Burton process have been made but all employing the basic principle of distillation under pressure maintained on both still and condenser. A 1925 estimate gives the number of Burton stills as about 1800, with an aggregate daily charging capacity of about 400,000 barrels per day yielding, perhaps, 120,000 barrels of gasoline per day.

Other than the Burton, there are four outstanding processes, judged from the standpoint of quantity of gasoline produced. An

[8] U. S. Patent 1,388,514, E. M. Clark.

estimate of the daily gasoline output from units now in operation and under construction would set this figure in the neighborhood of 30,000 barrels per day for each process or 120,000 for all four, which is the approximate figure for the Burton alone. These four processes are as follows, the order being alphabetical:

Process.	Owner.
Cross	Gasoline Products Company
Dubbs	Universal Oil Products Co.
Holmes-Manley	The Texas Company
Tube and Tank	Standard Oil Co. of New Jersey

The title of the last-named process would be equally appropriate for the other three, all four being similar in that cracking is effected by passing petroleum through a tubular heater to secure the desired necessary temperature and thence into one or more "pressure tanks" where the requisite time of reaction is possible. Differences in apparatus and method of operation form the basis of the various patents covering the different processes.

The Cross process is carried out in the form of apparatus shown in Fig. 3.

The heating and cracking coils are made up of steel tubes, 4 inches outside diameter, wall ½ inch thick. The pressure tank, called a "reaction chamber," is about 52 inches inside diameter; 42 feet long, with walls 5 inches thick. This reaction chamber is forged from a single steel billet. Cross units are operated at 650 to 700 lb. per square inch pressure on the reaction chamber and this pressure is released as the cracked oil or "synthetic crude" leaves the reaction chamber, through the pressure reduction valve. Cracking temperatures are of the order of 875° F. on the oil leaving the tube heater. The total volume of oil under pressure is about 40 barrels, which is very much less than that in the other processes. The time allowed for cracking in the reaction chamber is about thirty minutes. The balance of the apparatus is accessory equipment for the purpose of separating the "synthetic crude" into the desired products by utilizing its self-contained heat as it leaves the reaction chamber. In the Cross apparatus, the entire liquid (and gaseous) product leaves the reaction chamber through the pressure control valve and when pressure is released, most of the synthetic crude takes the vapor form. The vaporizer tower permits separation of the unvaporized liquid which is drawn off continuously from the bottom and delivered to fuel oil. The

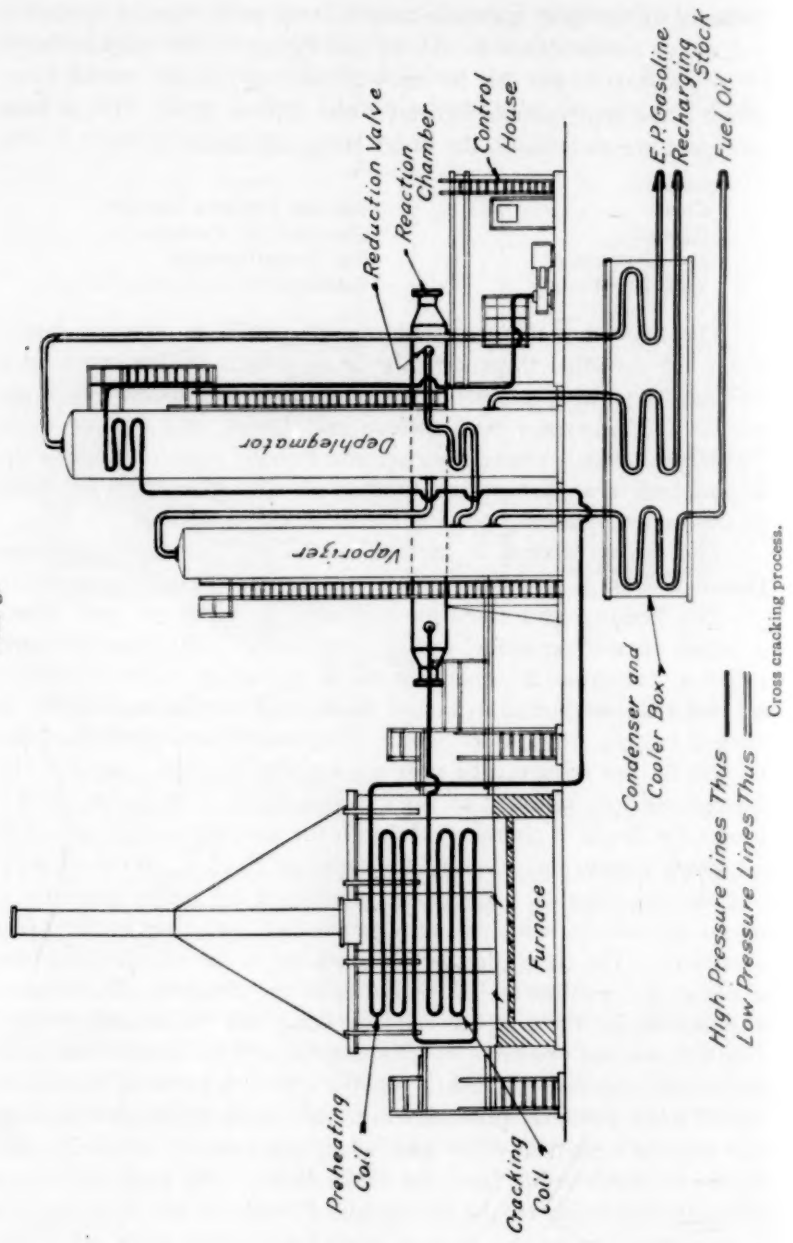

Reduction Valve
Reaction Chamber
Control House
E.P. Gasoline
Recharging Stock
Fuel Oil
Dephlegmator
Vaporizer
Condenser and Cooler Box
Furnace
Preheating Coil
Cracking Coil
High Pressure Lines Thus
Low Pressure Lines Thus
Cross cracking process.

FIG. 3.

vapors pass into the dephlegmating tower from which gasoline distillate emerges at the top in vapor phase, while a liquid condensate free from gasoline is continuously drawn from the bottom. This condensate is termed "recycle stock" and is normally pumped into the charging stock and again cracked. The gasoline vapors are condensed and require only a simple refining treatment to yield finished gasoline. The coke formed in the Cross process settles mostly in the reaction chamber but gradually builds up in the hottest parts of the tube heater, necessitating shut-down and cleaning after six to twelve days of continuous operation. The amount of carbon found is small, considerably less than 1 per cent., the major reason being that the charging stock is an overhead distillate from at least one distillation. Typical product yields from the Cross process are:

Charge: 44 per cent. fresh (uncracked) gas oil
56 per cent. recycle (cracked) stock

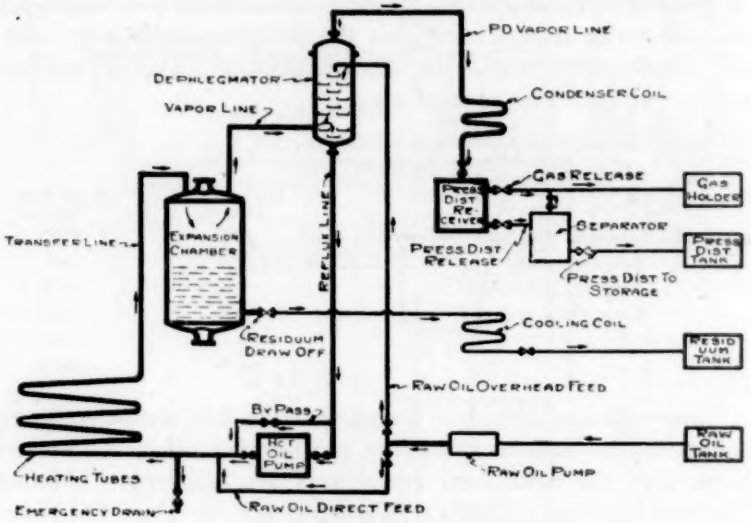
	From Total Charge.	From Fresh Charge.
Yields: Gasoline distillate 437° F. end point..	32%	72%
Recycle stock	56%	—
Fuel oil (residuum)	7%	16%
Loss, coke and gas	5%	12%
	100%	100%

Under efficient operation, the gas produced is almost sufficient to furnish the fuel required for heating the oil, provided, of course, that the usual heat exchangers are employed. Among American licensees of the Cross process are the Pure Oil Company, Shell Company, Standard of New York, Union Oil of California, Vacuum Oil Company, Solar Refining Company, Marland, Sun Oil Company, The Atlantic Refining Company, and others.

The "tube and tank" process of the Standard Oil Company of New Jersey is similar to the Cross. Oil is heated in a tube heater, then fed into pressure tanks, which are mounted in a vertical position and called "soaking drums." These correspond to the Cross "reaction chamber" but are considerably larger, being about 6 feet in diameter and 40 feet high with two "soaking drums" for each cracking unit. The usual pressure is about 350 lb. per square inch and the temperature about 860° F. Pressure is released as the cracked oil leaves the "soaking drums" and distilling equipment for separating this cracked product is similar

in principle to that outlined under the Cross process. Yields from the "tube and tank" process do not differ widely from those obtained by the Cross process when both operate on the same cracking stock. Due to the higher pressures employed, the Cross will give better results than the "tube and tank" on low-boiling distillate such as kerosene, while the tube and tank has some advantages over the Cross in that the large "soaking drums" permit cracking heavier stocks than those for which the Cross is designed. The Standard Oil of New Jersey and its subsidiaries

FIG. 4.



Flow chart of Dubbs' process.

are the largest users of the tube and tank process. The Tidewater Oil Company, Vacuum Oil Company, the Beacon Oil Company and others are among the licensees.

The Dubbs process owned by the Universal Oil Products Company is carried out in the apparatus shown in Fig. 4.

The fresh charging stock is pumped to a tube heater, some of it directly and some through the dephlegmator as shown. Recycle stock is not removed from the apparatus, but is pumped into the tube heater continuously by a hot oil pump. The pressure carried is about 150–200 lb. per square inch and the temperature is about 870° F. as in the two processes last described. The hot oil leaving the heater is discharged into the pressure tank,

called an "expansion chamber" in this process. Here tar and coke settle to the bottom and are drawn off continuously so long as possible. The vapors from the expansion chamber pass through a dephlegmator where there is further separation by fractional distillation into a recycle stock continuously fed back to the heater and vapors which are condensed by a water condenser yielding a pressure distillate containing about 75 per cent. of gasoline. The Dubbs process is used for cracking residual fuel oil as well as distillate gas oil. As with the other processes, yields depend on the charging stock and on the selected method of operation. In general Dubbs yields are somewhat above 50 per cent. of gasoline from gas oil and somewhat less from residual fuel oil. Some Dubbs units are operated so that no residuum is produced, the products being gas, naphtha distillate, and coke. The Dubbs expansion chamber is much larger than the corresponding pressure tanks of the other described processes. The usual diameter is 10 feet and the height varies from 15 feet to 30 feet. Such a pressure drum gives large coke-retaining capacity and this, together with the continuous recirculation of the recycle stock, permits cracking of heavy residual fuel as well as the cleaner distillate gas oils.

The Dubbs process is licensed to a large number of small refiners, while among the larger refineries are the Shell Company, Standard Oil Company of California, Producers and Refiners, Marland and the Pure Oil Company.

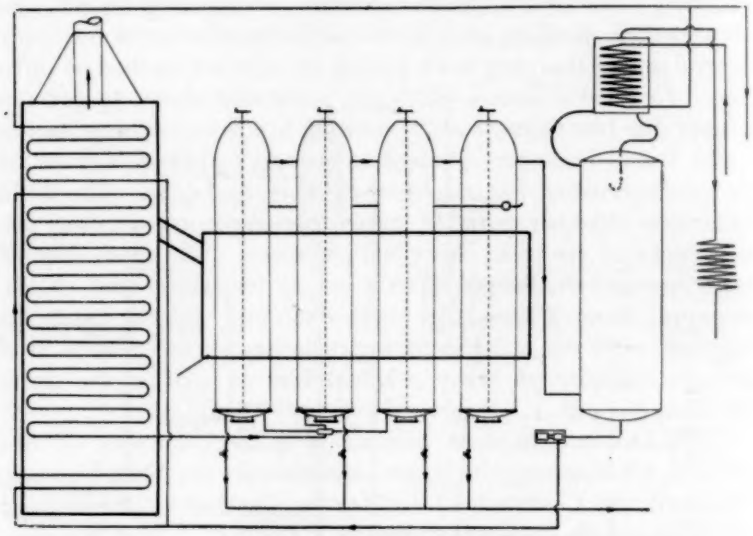
The Holmes-Manley process, owned by the Texas Company, might be called a "tube and four tank." The apparatus is shown in Fig. 5. A mixture of fresh charge and hot recycle stock is pumped through a tube heater in which its temperature is raised to about 800° F.[9] It then passes into four vertical stills, in the manner shown, these stills being set in a furnace and heated with small gas flames to maintain a temperature of approximately 775° F. The pressures are of the order of 350 lb. and still pressure is maintained on the condenser as in the Burton and Dubbs. The four vertical stills are equipped with carbon scrapers mounted on rotating vertical shafts. There are also liquid level equalizing lines between the stills, also vapor lines which carry the vapors from all four stills to a fractionating tower where recycle stock is condensed and returned to the tube heater while the gaso-

[9] R. C. HOLMES, *Nat. Pet. News*, pp. 61–62, March 10, 1926.

line vapors leaving the top of the fractionating tower are condensed by a water condenser. Tar is drawn from the bottom of the four stills at periodic intervals.

The Holmes-Manley apparatus permits extremely long runs without shutting down to clean. Operation for over twenty days is usual and some runs have lasted sixty days. Typical yields from

FIG. 5.



Holmes-Manley cracking apparatus.

mixtures of fresh gas oil and cycle gas oil obtained by redistillation of the pressure still bottoms are about as follows:

Charge:	Fresh gas oil	63%
	Cycle gas oil	37%

		From Total Charge.	From Fresh Charge.
Yield:	Gasoline distillate	46%	73%
	Cycle gas oil	37%	—
	Fuel oil	12%	19%
	Loss, coke and gas	5%	8%

The Texas Company is the largest user of the Holmes-Manley process, Standard of Indiana and Cities Service being among other licensees.

A description of the five most widely used cracking processes should be followed, logically at least, by a statement naming the

best one. Cracking processes, in some respects, are not unlike the automobile to which they owe their existence. Automobiles vary widely in initial cost; so do cracking processes, though through a relatively narrower range. Automobile repair bills vary, depending not only on the initial design and construction, but also upon the service and degree of care. The same applies to a cracking process. Furthermore, automobiles have not been perfected as indicated by the frequent changes in design and addition of accessory equipment. This applies in even greater degree to cracking process, and in general every cracking battery is built with some important changes from the previous model. The best cracking process is obviously the one which will convert cracking stock into more valuable products with the maximum profit. Such profit depends on many conditions which vary in different localities and at different periods. It is practically impossible to compare results, when available cracking stocks vary from kerosene to asphalt; when price considerations must cover different qualities of gas, gasoline, gas oil, fuel oil, coke and possible other by-products. The single item of fuel cost is an extremely important one and apparatus changes not directly involved in the cracking process have greatly reduced the original fuel cost in all processes, in fact heat conservation is no small factor in the present success of the art of cracking.

Cracking apparatus as employed commercially presents many interesting mechanical features. These include special furnace construction, special heater tubes, special forged return bends, box elbows, pressure control valves and many automatic devices. The combination of high pressure with temperatures of the order of 900° F. has presented many problems, the partial solution of which has demanded and attracted the skill and ingenuity of many engineers and the most exceptional of manufacturing equipment. The "soaking drums" in the "tube and tank" process are 6 feet in diameter, 40 feet long, made of eight sections of 2-inch steel plate rolled into rings, each ring with only one seam; rolls for 2-inch steel are only slightly more plentiful than the proverbial hen's-teeth. The Cross reaction chamber is of the seamless forged billet type; the current Cross units have reaction chambers 52 inches inside diameter, 42 feet long, walls 5 inches thick. They weigh over 60 tons; six of these reaction chambers now in use at a Philadelphia refinery were manufactured in the

Krupp Works at Essen, which less than a decade ago was building for action rather than reaction. Hot oil pumps to handle large volumes of oil at several hundred pounds pressure and at temperatures of 700° F. were not known until required for cracking processes. Tube cleaners for removing carbon are interesting adjuncts to cracking plants. Carbon and corrosion are the twin spectres that haunt the art. Corrosion troubles are met by extra thickness of metal, by use of special alloys, by admixture of lime with the charging stock and by rigid inspection and replacement, not *when* but *before* it is necessary. One of the Dubbs licensees is building an expansion chamber of unusual design, with the interior machine and electroplated with chromium, a decidedly costly operation.

There is a gravely involved patent situation as regards cracking. Various interests, engaged in developing the art, have naturally sought the fullest possible protection by patent. With over 2000 U. S. patents relating to cracking, it is not surprising that there are overlapping and conflicting claims. There is much litigation in progress with faint hope of any immediate adjudication. These legal controversies have not stopped developments in the cracking art nor do they appear to deter refiners from acquiring licenses under the named processes and others. Licenses are available at slightly varying rates, equivalent to about ¾ cent per gallon of gasoline made. New units are being erected not only in the United States, but in many foreign countries as well, Cross and Dubbs being foremost in the foreign field.

Inasmuch as gasoline is a material of so direct a personal interest to all of us to-day, it may not be amiss to pay some attention to the quality of gasoline, particularly gasoline from cracking processes. For many years, " cracked gasoline " was looked upon as a product very much inferior to straight run gasoline, that is, gasoline existing as such in crude petroleum and separated therefrom by simple distillation. A recent article [10] seems to be well worth quoting:

" There is an idea current among the jobbers, retailers and the general public that ' cracked ' or synthetic gasoline is an inferior motor fuel. This idea has been brought about by three principal factors. First, the name ' cracked ' implies an inferior product to the average man; second, undue criticism of synthetic

[10] O. C. SMITH, *Oil and Gas Jour.*, Dec. 3, 1925.

gasoline; third, the poor grade of synthetic gasoline as put on the market in the earlier days of cracking.

"It is to be lamented that the word 'cracked' gasoline was ever popularly applied as the name of the product made by the progenic treatment of heavy petroleum products. The very name 'cracked' itself gives to the average person the idea that the gasoline is about one-half burnt up. He thinks that something has been broken and that it is necessarily not as good as that obtained naturally from the crude. This, of course, is not true.

"We are using synthetic products in every walk of life and nobody thinks anything about it. In prehistoric days the women combed their hair with the backbone of a fish. This we will call a straight run comb. But to-day none of the ladies, we believe, would be satisfied to have a fish bone lying on her dressing table with which to comb her hair. They prefer the synthetic comb made of bakelite, a synthetic resin, or pyralin which is made from cotton. We have to-day artificial or synthetic pearls which are as beautiful as the natural or straight run pearl. Some of the most beautiful dress goods are made from wood and sold under the trade name of rayon.

"In each of these cases, there is a cracking or breaking up of one substance to form a new one. The same thing occurs in the manufacture of synthetic gasoline. It is broken or cracked and changed from one compound into another. It is perfectly easy for some of the people who are so adverse to using synthetic gasoline to get a straight run cane by going into the woods and finding some crooked limb of a tree which would possibly serve them, but most of them would prefer the beautiful synthetic cane, finely polished and finished, with the ornamental handle and gold tip."

The article just quoted is pregnant with ideas of evolution. Tracing the evolution of gasoline standards, the following facts are outstanding:

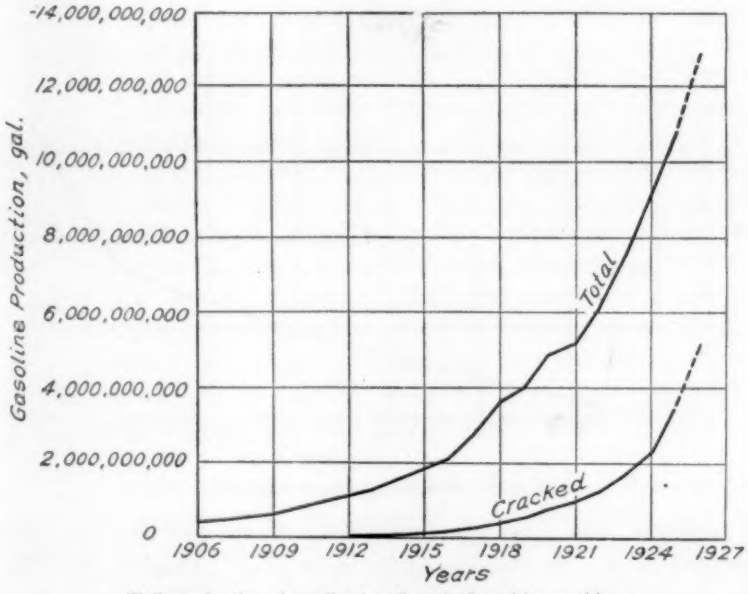
The first criterion of gasoline quality was gravity. At that time gasoline was made from comparatively few crudes and those of the same general chemical type and all gasoline was "straight run." Under these conditions, gravity did furnish some basis for judging quality. With the advent of natural gas gasoline, then known as casinghead gasoline, it became possible to mix this very light gravity material with high boiling-point naphtha and

even with kerosene and to obtain gravities which were considered standard by the consumer. Many such mixtures were unsatisfactory motor fuels though the gravity was right. On the other hand, after the discovery and utilization of new crude petroleums, gasolines of heavy gravity were found by the motorist to be highly satisfactory. The gravity criterion has, therefore, become obsolete.

Next came the distillation specification which is distinctly more rational than gravity because such distillation does indicate, *when properly interpreted,* the ease and completeness with which a given gasoline will vaporize. While the distillation specification is still used and forms the main part of our present Federal specification for motor gasoline, nevertheless it is no longer adequate, and is likely to be misleading. Two gasolines may have the same distillation curves and yet be distinctly different as motor fuels. The reason is that motor fuel must not only vaporize, that is change its physical state, but before it can do work, it must be burned, that is, undergo a chemical change. It is to the chemical reactions involved in burning gasoline that petroleum chemists and automotive engineers have been turning their attention during the last five years. It is well known that higher fuel efficiency in the gasoline engine can be obtained by the use of higher compression. It is also well known that the average gasoline of five years ago knocked badly or detonated in a high-compression motor. Detonation, accompanied when severe by loss of power, has prevented engine builders from putting out the most efficient engines they knew how to build, because the efficient high-compression motor is both inefficient and unpleasant when its fuel is detonating. Furthermore, fuels for all motors must be widely distributed in these days when distance is almost annihilated. Petroleum refiners, therefore, have faced the problem of supplying fuel not only for the enormous number of low-compression motors in use, but also for those of higher compression which represent the automotive engineer's effort toward greater fuel efficiency and economy. In solving this problem both petroleum chemist and automotive engineer have found that the distillation specification is inadequate as is to be expected since distillation characteristics throw no light on the power-yielding value of the fuel. This appears to be a function of the manner in which the fuel burns and is intimately linked with the chemical nature of the hydrocarbons that make up the fuel.

A few individuals advocate chemical specifications to ensure proper burning quality in gasoline. At the present time, such tests are too elaborate, too long, too inaccurate, and too indecisive to justify more than scientific interest and study. The direct criterion of burning quality now appears to be a measurement, not of cause but of effect, namely, actual test in a suitable test engine under standardized conditions. Such a test is not unlikely to supplement and later displace the present distillation test.

FIG. 6.



U. S. production of gasoline by all methods and by cracking.

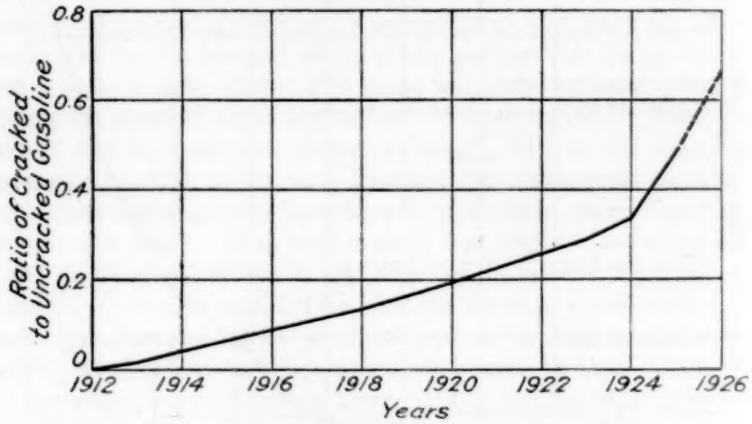
In motor tests, cracked gasolines, when suitably refined, are found to be superior to straight run gasolines from many, if not most, crude petroleums. Cracked gasoline in general is capable of burning in an automotive engine without detonation at pressures distinctly higher than is straight run gasoline from Pennsylvania or Mid-Continent crudes. It is most fortunate for the American public that our increasing motor fuel requirements are being augmented with cracked gasoline.

Fig. 6 shows that United States production has greatly increased both for total gasoline and for cracked gasoline, the

values for the latter being estimated. Fig. 7 shows the increase in ratio of cracked to uncracked gasoline.

That the cracking of petroleum to produce gasoline is now firmly established quantitatively must be apparent to all of you. The quality of gasoline must be judged not by gravity, not entirely by distillation, but principally by motor performance. From such considerations, cracked gasoline, when suitably refined, will pass the most careful scrutiny. Last fall our own Bureau of Standards made engine tests on two gasolines, one of which, called

FIG. 7.



Increase in proportion of cracked gasoline.

Y Gasoline, was a straight run Mid-Continent gasoline; the other denoted by X was gasoline made from Mid-Continent gas oil by the Cross process. Quoting the report of the Bureau of Standards [11]: "The anti-knock value of X Gasoline is 19 per cent. higher than the anti-knock value of Y Gasoline." Similar findings are reported by other laboratories on cracked gasoline from other cracking processes. It is becoming more and more evident from confirmatory data that development of the art of cracking is placing at our disposal a synthetic, man-made gasoline which is superior qualitatively as well as quantitatively to that which nature made in bygone eons.

[11] *Oil and Gas Jour.*, Nov. 26, 1925.

THE CONTRAST OF PHOTOGRAPHIC PRINTING PAPER.*†

BY

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SECTION C. SENSITOMETRIC RESULTS.

THE statistical work has yielded reliable values which completely specify the characteristics of the negative (for the particular test-object chosen) which on each of the different printing papers give the best possible print quality. These values of themselves are not adequate for the computation of the *contrast* of the positive materials. This is conclusively demonstrated by the fact that the same *optimal negative* is required by positive materials differing widely in that characteristic commonly designated as *contrast*. There seems, therefore, to be no possibility of a general correlation between the *contrast of the positive material*, or of the *optimal positive* made thereon, and the contrast of the *optimal negative*. Since the brightness scale, BS_0, of the object is the same for all of the negatives, the addition of this value to those specifying the negative characteristics is of no assistance. It is evident, therefore, that it is necessary to rely upon information obtained by sensitometric methods for the evaluation of contrast.

The values obtained statistically do, however, when combined with the sensitometric data, enable us to determine just what portion of the characteristic curve of the positive material is utilized in obtaining the *optimal positives*. By applying the contrast formula to the portion of the curve used, it is then possible to obtain for the various materials, values which represent the contrast available in the reproduction of any object brightness scale (BS_0) equal to that of the "Willow Pond" test-object (Fig. 5) used in the statistical determination of the optimal negative values.

It is a relatively simple matter to determine the characteristic

* Communicated by Dr. C. E. K. Mees, Director of Laboratory, and published as Communication No. 264 from the Research Laboratory of the Eastman Kodak Company.

† Continued from p. 516 of the October issue.

curve of a developing-out paper, and this can be accomplished with a very satisfactory degree of precision. It is only necessary to expose the sample of paper in the sensitometer, develop under standard conditions, read the resultant densities, and plot these density values against log exposure. A typical example of such a curve was shown in Fig. 2.

When this work was started, the necessity of sensitometric information was anticipated and careful measurements of this kind were made on all of the materials used in the statistical work. In this section, a detailed account of this sensitometric work, together with the final constants computed therefrom and used to express the characteristics of these papers in numerical terms, is given.

In a paper published in 1914 [1] the subject of sensitometry of photographic papers was dealt with in detail. Previous to this Renwick,[18] in a paper dealing with the under-exposure region of the characteristic curve, had determined the relation between the densities of a series of silver deposits on a transparent base (glass) as measured by transmitted light, and the densities of the same deposits with matte white opal glass. Density as measured by reflected light was defined as $\log \frac{R}{r}$, where r is the reflection factor of the deposit and R that of the opal glass support. He did not, however, apply the method to the determination of the sensitometric characteristics of positive materials. His conclusions (drawn from the results of measurements made on deposits supported on glass placed in contact with white opal and then illuminated through the transparent glass cover) that the density (reflection) obtainable with silver deposits on white opaque surfaces, such as are used in the manufacture of developing-out papers, cannot exceed 1.48, are not supported by our experimental results. There are many glossy-surface developing-out papers which give maximum densities of 1.7, and with ferrotyped samples values as high as 2.00 have been observed, thus showing that in the case of such positive materials the ratio of maximum to minimum brightness may be 50 ($D = 1.70$), or even under most favorable conditions as high as 100 ($D = 2.00$). Renwick's definition of the density silver deposits viewed by reflected light is thoroughly sound from both the theoretical and practical standpoints, and this was adopted in our work on the subject. Since

the publication of our previous work (*loc. cit.*) several papers [34, 35, 36] have appeared in the literature dealing with the general subject of paper sensitometry, but practically no additions worthy of note have been made.

The sensitometric exposures were made in an instrument [37] constructed for this purpose, giving a series of exposures increasing by consecutive powers of the cube root of 2 on the time-scale basis. Five strips of each of the papers used in the statistical work were thus exposed, and from the mean values of densities determined therefrom the sensitometric curve representing the characteristics of each of the materials used was plotted. The exposed strips were developed in a solution compounded according to the formula recommended by the maker of the paper and identical with the developing solution used in developing the prints in the statistical study. The temperature of the developer was kept constant throughout development at 20° C. The time of development was made sufficiently long so that it could be controlled precisely, and was identical with the time of development used in making the prints.

The density measurements were made with the instrument previously described [1] which is a modified Bechstein photometer. The surface carrying the deposit is illuminated with light incident at an angle of 45 degrees from the normal to the plane of the surface and is observed normally (line of sight perpendicular to the surface). Thus the specular component of the reflected light is eliminated and the value obtained is that of the diffuse reflection factor. During measurements the sample is supported in a rigid holder so that the geometrical conditions of illumination and observation specified above are precisely fulfilled. An area (of the positive material under test) which has received no exposure, but which has been developed for the same time and has been subjected to the same treatment in fixing, washing, and drying, etc., as the densities to be measured, is assumed to have a diffuse reflection factor of 100 per cent. ($D = 0$). Any fog which may be inherent in the positive material is thus subtracted. This convention has been adopted as *standard practice* because densities expressed on this basis correctly represent the visual contrast existing in a print made on the material, assuming, of course, that the print is subjected to the same processing, development, fixing, washing, etc., as the sensitometric strip.

For certain purposes it may be more useful to adopt some other standard for reference, such, for instance, as a magnesium carbonate surface for which the commonly accepted value of diffuse reflection factor is 98 per cent. If this is done the densities are then expressed in absolute terms. In other cases it may be more satisfactory to use as a basis of reference a portion of the sensitive material which has been fixed out without development. Density readings made in this way include the inherent emulsion fog and this is sometimes of use where it is desired to determine in what way the fog depends upon various factors in processing. However, unless otherwise specified, all density values given in this paper are in terms of the *standard practice* as defined above.

The great care exercised throughout in keeping all conditions under which sensitometric measurements were made identical with those used in making prints, and the averaging of results from five independent sensitometric tests, insures that the sensitometric curves obtained represent with a high degree of precision, the sensitometric characteristics of the papers as used in making the prints.

I. ERRORS INVOLVED IN DETERMINATION OF CHARACTERISTIC CURVE.

Every physical measurement is subject to some uncertainty or error and it is advisable before proceeding further to consider the causes and magnitude of the unavoidable errors involved in the establishment of the characteristic curves of positive materials. The chief sources of error may be classified as follows:

1. *Error Involved in the Measurement of Density.*—This error will be designated as *reading error* and in the discussion and tabulated data following, will be designated by the symbol, a.

$$\textit{Reading error} = a.$$

2. *Error Arising from Local Variations in the Effective Sensitivity of the Positive Material.*—While these errors are so small as to be of little importance in the practical work for which these materials are designed, they must be recognized and considered in cases where precise quantitative measurements are made. Such errors may occur as a result of lack of uniformity in thickness of the sensitive coating, as a result of the variations in the inherent sensitivity of the material, or as a result of local variations in the physical condition of the material at the time of exposure. No

attempt will be made to separate these factors, but the error arising from a combination of all such peculiarities will be referred to as the *non-uniformity error* and designated as *b*.

Non-uniformity error = *b*.

3. *Errors Arising from Variations in Processing (Development, Fixing, Washing, Drying, Etc.) of the Exposed Material.*—This will be termed the *processing error* and designated as *c*.

Processing error = *c*.

4. *Error Resulting from Variations in the Magnitude of the Exposure.*—In making the sensitometric exposures every precaution was taken to eliminate this error, and, as is shown by the results given later, very little error attributable to this cause was present. The time factor exposure was controlled by a governed motor operating at constant speed, and the variation in the speed of this motor was known to be less than ± 1 per cent. The incandescent lamps used as source of light were carefully seasoned, standardized and operated at constant current. Error due to these causes will be referred to as *exposure error*.

Exposure error = *d*.

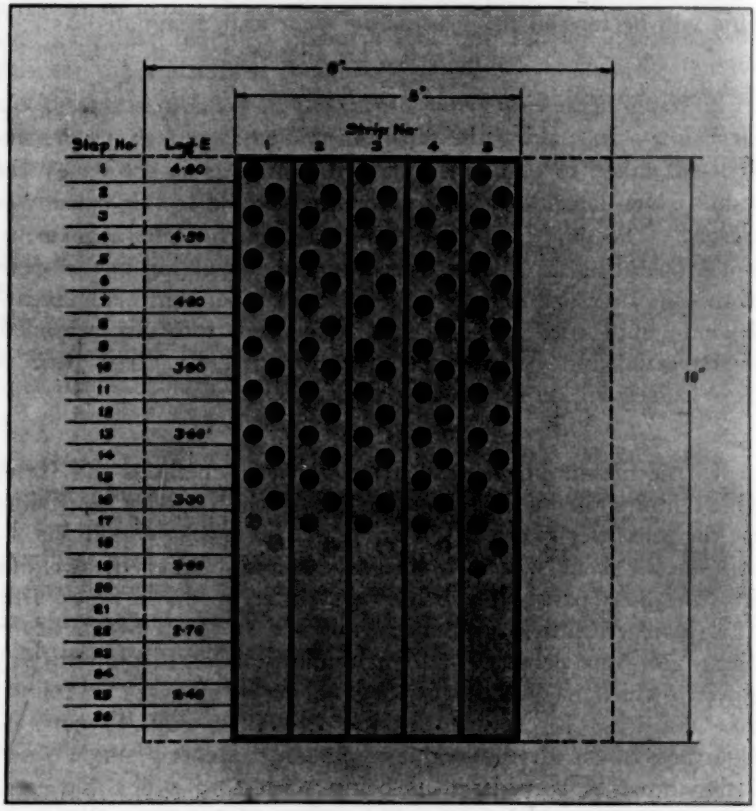
In the measurement of density by visual methods the factor which limits the precision obtainable is the contrast sensibility of the observer's eye. Under most favorable conditions of photometric field size, field brightness and quality of dividing line, the just perceptible brightness difference is 1.7 per cent. This just perceptible difference expressed in terms of density is .0074. and since density is a logarithmic function of the reflecting power (which is directly proportional to brightness) it follows that the least perceptible density difference, $\triangle D$, is constant regardless of the absolute value of density. Hence a single observation must be considered as being subject to a possible error of 1.7 per cent., which expressed in terms of density is $D = .0074$. The probable error in the determination of density can be greatly reduced by making a large number of measurements of each density and taking the arithmetical mean as the most probable value.

There seems to be no method of estimating, *a priori*, the magnitude of the errors arising from non-uniformity, exposure, and processing. It is necessary, therefore, to resort to experimental tests designed specifically to make possible their evaluation.

The experimental procedure and results of this work are given in the following pages.

Group A—Reading Error (a) and Non-uniformity Error (b).—The procedure followed in the measurement of these errors can best be explained by reference to Fig. 17. From the central

FIG. 17.



Illustrating the method of making the sensitometric exposures for the determination of the magnitude of the experimental errors involved in the sensitometry of developing-out papers.

portion of an 8 × 10 sheet of positive material a strip 3.75 inches wide was cut. This was placed in the sensitometer and exposed in the usual manner, the exposures given being indicated by the number in the log E column in the figure. From this exposed material it is possible to cut five complete sensitometric strips as indicated in the figure. The exposure was adjusted so as to give,

with the material being used, the maximum density on step No. 1. These strips when developed gave twenty-one steps showing measurable densities. After exposure, the entire sample was processed in the usual manner, and after drying was cut into five strips, as indicated by the numbers at the top of the figure.

One set of readings was made on each of the five strips, and this was repeated on other days until five complete sets of

TABLE XIX.

Values of Density Obtained by Measuring the Same Sensitometric Strip Five Different Times. These Values Are Used in Computing the Reading Error.

Density Values, Strip No. 2.							Error.
Step No.	March 6.	March 10.	March 12.	March 16.	March 23.	Mean.	*A.*
1	1.30	1.29	1.32	1.33	1.30	1.31	.007
2	1.30	1.29	1.31	1.30	1.30	1.30	.002
3	1.27	1.29	1.29	1.27	1.29	1.28	.005
4	1.25	1.25	1.25	1.25	1.28	1.26	.006
5	1.21	1.21	1.21	1.21	1.21	1.21	.000
6	1.14	1.15	1.13	1.13	1.16	1.14	.005
7	1.08	1.09	1.09	1.10	1.06	1.08	.006
8	1.00	1.03	1.03	1.05	1.04	1.03	.006
9	.94	.96	.96	.98	.95	.96	.005
10	.88	.90	.88	.88	.88	.88	.002
11	.84	.85	.84	.83	.86	.84	.004
12	.77	.77	.76	.75	.75	.76	.004
13	.67	.68	.65	.67	.67	.67	.003
14	.54	.55	.54	.53	.55	.54	.003
15	.40	.43	.42	.42	.40	.41	.005
16	.31	.33	.29	.30	.31	.31	.005
17	.22	.22	.21	.23	.22	.22	.002
18	.13	.16	.14	.15	.14	.14	.004
19	.08	.09	.09	.08	.07	.07	.006
20	.04	.05	.04	.04	.05	.04	.002
21	.02	.02	.03	.02	.03	.02	.002
					Mean "average error"		.0040

readings had been made. The five independent readings on the same strip may now be used for the evaluation of the reading error (a), while the five groups of readings on the different strips may be used for the evaluation of the non-uniformity error for an area of this size. It is evident that these values afford no information as to the existence of any non-uniformity in the direction of the greater dimension of the strip, but they do indicate the extent of lateral non-uniformity. In Table XIX are given the density values obtained for strip No. 2 on the five different days as indicated, and in the column designated as *mean* will be found the mean density value for each step. It will be noted that

there are measurable deviations between this mean and the individual density readings, and upon these deviations is based the evaluation of the reading error.

There are several different methods in common use for the computation of error and it was necessary to choose the one best suited for the purposes of this work. The probable error, computed on the basis of least squares, has no significance when the number of observations averaged is small. It, therefore, does not seem advisable, for the purposes of this problem, to use the probable error. The *average error* or "mean of the errors" seems much better adapted to our purposes. According to Mellor,[38] "the *average error* measures the average deviation of each observation from the mean of the whole series. It is a more useful standard of comparison than the probable error when the attention is directed to the relative accuracy of the individual observations in this series of observations. The average error depends not only upon the *proportion* in which the errors of different magnitude occur, but also on the *magnitude* of the individual errors." The average error is computed according to the following equations:

Let: ΔD = The deviation of a single observation from the arithmetical mean of the group.
n = Number of observations.
$\Sigma(+\Delta D)$ = Sum of the deviations of every observation from the mean, their sign being disregarded.
r = *Average error* of a single observation.
A = *Average error* of the arithmetical mean of the whole series (n) of observations.
x = Arithmetical mean of the deviations.

$$x = \frac{\Sigma(+\Delta D)}{n} \tag{1}$$

$$r = .8454x \tag{2}$$

$$A = \pm \frac{\Sigma(+\Delta D)}{n\sqrt{n}}. \tag{3}$$

In Table XX are shown the deviations of the individual density measurements from the mean of the series for each step. The values of $\Sigma\Delta D$ are in the column thus designated, and the mean of the deviations $\left(\frac{\Sigma(+\Delta D)}{n}\right)$ in the column x. In the last column are the values of r, the *average error* applying to the individual density readings shown in Table XIX.

Using equation (3) above, the values of A, Table XIX, were computed. These are the *average errors* applying to each mean of five observations for each step. The mean *average error*, A,

TABLE XX.

Values of $\triangle D$, the Density Difference between Individual Values and the Mean of Five Independent Readings.

Step No.	$\triangle D$.					Sum. Mean Av. Error.		
	March 6.	March 10.	March 12.	March 16.	March 23.	$\Sigma\triangle D$.	s.	r.
1	.01	.02	.01	.02	.01	.07	014	.012
2	.00	.01	.01	.00	.00	.02	.004	.003
3	.01	.01	.01	.01	.01	.05	.010	.008
4	.01	.01	.01	.01	.02	.06	.012	.010
5	.00	.00	.00	.00	.00	.00	.000	.000
6	.00	.01	.01	.01	.02	.05	.010	.008
7	.00	.01	.01	.02	.02	.06	.012	.010
8	.03	.00	.00	.02	.01	.06	.012	.010
9	.02	.00	.00	.02	.01	.05	.010	.008
10	.00	.02	.00	.00	.00	.02	.004	.003
11	.00	.01	.00	.01	.02	.04	.008	.007
12	.01	.01	.00	.01	.01	.04	.008	.007
13	.00	.01	.02	.00	.00	.03	.006	.005
14	.00	.01	.00	.01	.01	.03	.006	.005
15	.01	.02	.01	.01	.00	.05	.010	.008
16	.00	.02	.02	.01	.00	.05	.010	.008
17	.00	.00	.01	.01	.00	.02	.004	.003
18	.01	.02	.00	.01	.00	.04	.008	.007
19	.01	.02	.02	.01	.00	.06	.012	.010
20	.00	.01	.00	.00	.01	.02	.004	.003
21	.00	.00	.01	.00	.01	.02	.004	.003
						Mean "average error"		.0066

as determined for all of the twenty-one steps, is shown at the bottom of the table and is .0040. This is remarkably small and

TABLE XXI.

Summary of the Errors Due to Reading.

Strip.	A.	r.	Type of Error.
1	.0054	.0092	*a*
2	.0040	.0066	*a*
3	.0047	.0080	*a*
4	.0051	.0087	*a*
5	.0051	.0087	*a*
Mean	.0049	.0082	*a*

shows that a curve plotted from the mean of five strips is established with a very high degree of precision. The mean average error applying to the individual readings is found to be .0066.

It should be kept in mind that the errors evaluated in this way give only the uncertainty arising from the measurement of density. In a similar manner the mean values of A and r can be found for each of the five strips, and in Table XXI these results are summarized. Basing the determination upon five independent groups of readings, the final values for A and r attributable to the reading error are found and shown at the bottom of the table.

Now if the readings made on *each* of the five strips be taken as a group, it is possible to evaluate the magnitude of the non-uniformity error. Treating these density readings in an exactly similar manner, the values shown in Table XXII were obtained. The values of A and r now represent the error which is attributable to both reading and non-uniformity and by subtracting the

TABLE XXII.

Summary of the Errors Attributable to Reading and Non-uniformity.

Date.	A.	r.	Type of Error.
March 6	.0042	.0072	$a+b$
March 10	.0054	.0092	$a+b$
March 12	.0061	.0108	$a+b$
March 16	.0051	.0085	$a+b$
March 23	.0055	.0093	$a+b$
Mean	.0053	.0092	$a+b$
	.0049	.0082	a (mean from Table XXI)
	.0004	.0010	b (mean)

mean value of the reading error (a) it is possible to isolate the uncertainty due to non-uniformity (b). These values are shown at the bottom of Table XXII. It is interesting to note that the extent of lateral non-uniformity in a sample of material of the size used is practically negligible as compared with the reading error.

Group B—Processing Error (c).—Having established the magnitude of the reading error and the lateral non-uniformity error for a sample of the size shown in Fig. 17, it is now possible to determine the magnitude of the processing error (c). A sample of the same size was again taken and exposed as previously. After exposure this was cut into five strips and each strip was processed separately. For this purpose a separate mixing of developing solution was made for each strip and the processing was carried out in such a way that the maximum probable

variation of conditions used in sensitometric work was realized. One set of density readings was made on each strip and the values treated as in the determination of reading error. The results are shown in the first section of Table XXIII. The values of average error, A and r, now include the errors due to reading, non-uniformity, and processing $(a + b + c)$. The values of A and r obtained are remarkably small, in fact they are less than the mean error due to reading and non-uniformity $(a + b)$ shown in Table XXII. They are, however, greater than the minimum error attributable to those causes. If we assume that the reading

TABLE XXIII.

Summary of the Errors Due to Various Sources.

Section.	A.	r.	Type of Error.
I	.0046	.0078	$a+b+c$
	.0042	.0072	$a+b$ (mean, Table XXII)
	.0004	.0006	c
II	.0062	.0105	$a+b+d$
	.0053	.0092	$a+b$ (mean, Table XXII)
	.0009	.0013	d
III	.0083	.0141	$a+b+c+d$
	.0053	.0092	$a+b$ (mean, Table XXII)
	.0030	.0049	$c+d$
	.0010	.0016	c
	.0020	.0032	d
IV	.0061	.0103	$a+b$ for five sheets
	.0049	.0082	a (Table XXI)
	.0012	.0021	b for five sheets

and non-uniformity error in the case of these strips was the same as that found previously for the group read on March 6th (Table XXII), we then have the residual processing error (c) shown in the first section of Table XXIII. This value is remarkably small, and it should be kept in mind that it is based only on a single group of strips. Had this been repeated several times, as in the work for reading and non-uniformity error, it is probable that a somewhat higher value would have been obtained. However, the work done indicates that the processing error is so small as to be of little importance.

Group C—Exposure Error (d).—In order to determine this factor the five strips, as shown in Fig. 17, were cut from the

sheet and each strip exposed separately in the sensitometer. The same care in regulation of lamp current and motor speed was taken as is normally exercised in the exposures of sensitometric strips. After exposure these five strips were assembled side by side and given identical treatment in processing. One set of density readings was made on each strip and the values of average error computed as previously. The results are shown in the second section of Table XXIII. The values A and r thus determined include the reading, non-uniformity, and exposure error $(a + b + d)$, and by subtracting the mean error $(a + b)$ found in Table XXII, the residual attributable to exposure is found. This also is remarkably small as compared with the reading error.

Group D—Total Error $(a + b + c + d)$.—Five strips were again cut, as shown in Fig. 17, and exposed separately. These were then processed separately and the density readings made as before. The average errors A and r determined from this group include the error $(a + b + c + d)$ and the values obtained are shown in the third section of Table XXIII. Subtracting the mean error due to reading and non-uniformity the residual $(c + d)$ is found. This is somewhat greater than the sum of the c and d errors shown in the first and second sections of this table, and if we divide the residual $c + d$ in the third section in the same proportion as that existing between the values already determined, the relative amount of error attributable to c and d is as shown.

Group E—Non-uniformity in the Case of Different Samples of the Same Material.—One sensitometric strip was cut from each of five different sheets of positive material taken from the same package. These were exposed and processed together, and it is assumed that this procedure eliminates the errors due to those causes. The density readings treated as previously give values of A and r as shown in the fourth section of Table XXIII. If we subtract the mean value of error a as determined in Table XXI, a residual for b in the case of five different sheets of material is as shown. This is very small and again practically negligible as compared with the reading error.

From this careful analysis of the magnitude of error attributable to various steps in the determination of the sensitometric curve, it is evident that the reading error is of greatest magnitude. The total error from all causes is, however, very small, and if

the sensitometric curve is plotted from the mean of five sensitometric strips, its position and shape are determined with great certainty. The allowance of an *average error* value of ± .01 is ample for such cases, while if the curve is based upon the readings from a single strip, this must be increased to ± .015. All of the sensitometric curves used in this work are based on a mean obtained from five strips, and hence the density values used are subject to an *average error* of only ± .01. It should be noted, as is shown by the values in Tables XIX and XX, that the magnitude of the *average error* is practically independent of the absolute magnitude of density. This is to be expected when it is considered that a constant $\triangle D$ corresponds to a constant percentage difference in brightness which is the controlling factor in the process of photometric measurements.

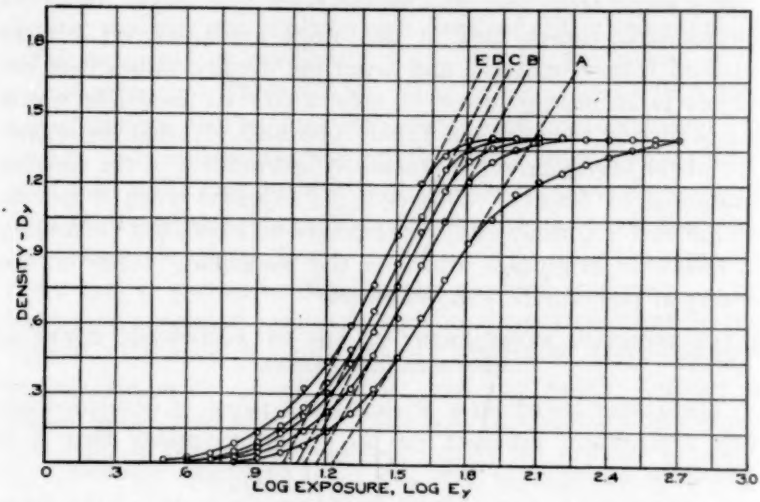
II. THE EFFECT OF DEVELOPMENT ON THE CHARACTERISTIC CURVE OF PHOTOGRAPHIC PAPERS.

The extent to which a photographic paper is developed has such a profound influence on the resulting quality that it is considered advisable to give this point particular attention. As was pointed out at some length in the previous paper,[1] the shape of the characteristic curve is vitally dependent upon the extent of development and this dependence varies greatly for different types of developing-out papers. The decision as to the development time to use in making the prints and sensitometric strips depends upon a knowledge of the time required for each type of positive material and the developing solution used therewith, to obtain a *condition of equilibrium* as judged by the *shape* of the characteristic curve.

In Fig. 18 is shown a group of curves obtained with the developing-out paper designated as No. 6 in the previous section. This is typical of the Azo group of papers, Nos. 1 to 13, inclusive. It should not be understood that all papers of this group develop exactly as indicated in Fig. 18, but this particular one was chosen as being typical of the group of papers. The development times used in obtaining this group of curves and those shown in succeeding figures (16 to 20, inclusive) are given in the first column of Table XXIV (T_d minutes). Curve *A*, obtained with a development time of thirty seconds, shows that maximum black

has not been reached, nor has gamma attained its maximum value. It is evident, therefore, that with this time of development, the material, from the standpoint of photographic quality,

FIG. 18.



Group of sensitometric curves showing change of shape with time of development for papers of the Azo type.

has not reached a condition of equilibrium. In the case of curve *B*, obtained with a development time of forty-five seconds, gamma

TABLE XXIV.

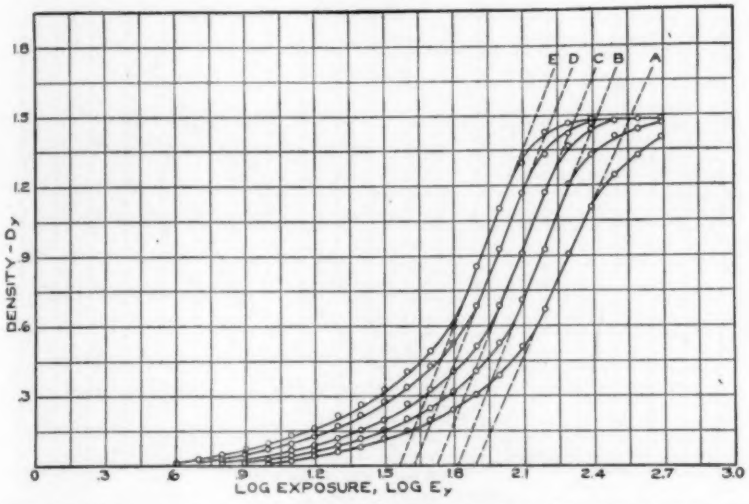
Dependence of Gamma on the Time of Development for Developing-out Papers of Various Types.

T_d (min.).	Paper No. 6 Azo (Fig. 18).		Paper No. 17 Velox (Fig. 19).		Paper No. 22 Artura Iris (Fig. 20).		Paper No. 27 Artura N. C. (Fig. 21).		Paper No. 36 Bromide. (Fig. 22).	
	Curve.	γ_y.	Curve.	γ_y.	Curve.	γ_y.	Curve.	γ_y.	Curve.	γ_y.
.25			*A*	2.00						
.50	*A*	1.70	*B*	2.20	*A*		*A*		*A*	.68
.75	*B*	2.20	*C*	2.26	*B*		*B*		*B*	1.00
1.00	*C*	2.29	*D*	2.26	*C*		*C*	1.37	*C*	1.28
2.00	*D*	2.29	*E*	2.26	*D*	1.23	*D*	1.37	*D*	1.41
3.00	*E*	2.29								
4.00					*E*	1.23	*E*	1.37	*E*	1.41

has not quite reached its maximum value nor has the upper portion of the curve attained its final shape. Within the limits of experimental error, curves *C*, *D*, and *E* are identical in *shape*. For

times of development greater than one minute, there is no change in the *shape* of the curve, but there is a lateral shift in the curve which in effect is equivalent to an increase of exposure. For this group of papers, therefore, a development time of two minutes was used. This is well in excess of the minimum time required to obtain the final shape and the rate of lateral shift of the curve relative to the exposure axis has decreased so that small variations in the time of development will have but little effect upon the *shape* and *position* of the curve. For the Azo group,

FIG. 19.



Group of sensitometric curves showing change of shape with time of development for papers of the Velox type.

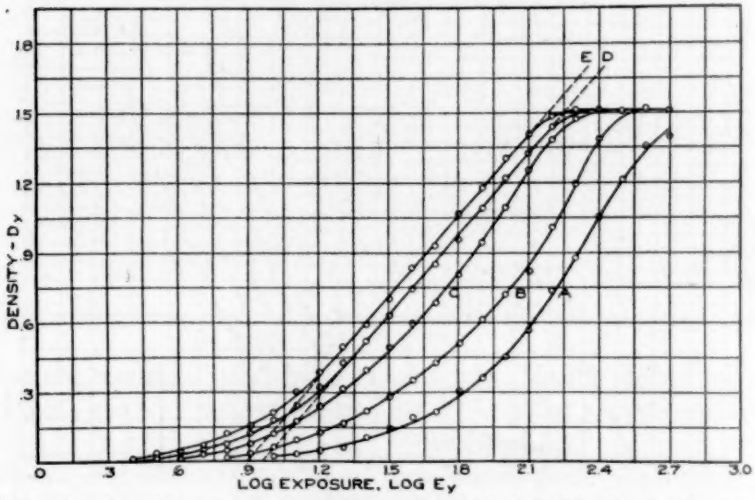
Nos. 1 to 13, development time of two minutes was employed in making both the sensitometric strips and the prints.

The manner in which the papers of the Velox group, Nos. 14 to 20, inclusive, develop, is illustrated by the curves in Fig. 19. In this case curve *A* is obtained with a development time of fifteen seconds (.25 minute). It is evident that these papers develop much more rapidly than those of the group previously discussed. Curve *B*, which was obtained with the development time of thirty seconds, has a gamma value of 2.20, which is very near to the maximum value of 2.26 obtained at forty-five seconds. Curve *C* ($T_d = 45$ seconds) shows that the material has reached an equilibrium with respect to the *shape* of the characteristic curve, and

the effect of further development is to shift the curve laterally relative to the exposure axis. For the papers of this group, therefore, a development time of one minute was used in making both the sensitometric strips and the prints.

It should be noted that none of the development times employed in making the curves in Fig. 19 were sufficiently long to result in the production of any appreciable development fog. This is shown by the fact that the maximum density for the curves of longer development time has not decreased perceptibly. All

FIG. 20.



Group of sensitometric curves showing change of shape with time of development for papers of the Artura Iris type.

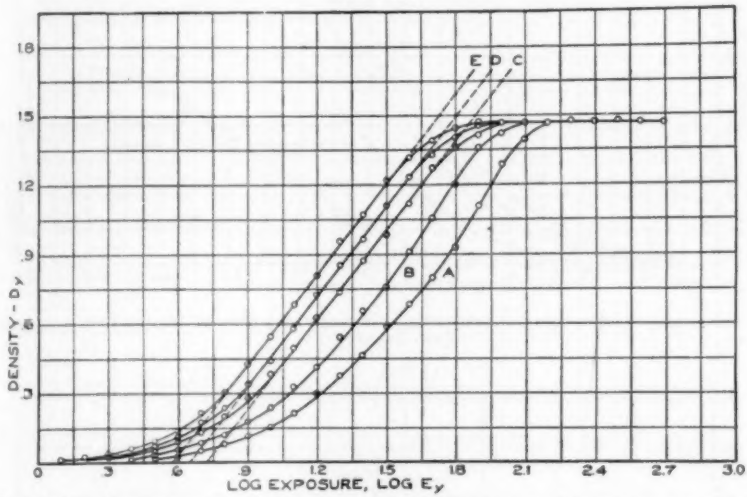
density measurements were made with reference to an area of the sensitometric strip which had received no exposure but had been subjected to the same treatment in development, fixing, washing, etc., as the exposed areas. That is the density of such an area was assumed to be zero (reflection factor = 100 per cent.), and in making the density measurements such an area was placed in the densitometer and the instrument set to read $D = 0$. The appearance of development fog, therefore, is shown in the resultant curve by the apparent depression of maximum black. It will be noted that in none of the curves shown in Figs. 18 to 22, inclusive, is such an effect visible.

The curves in Fig. 20 show the way in which development

proceeds in the case of the Artura Iris group (Nos. 22 to 24). For the shorter times of development there is no portion of the curve which can be represented by a straight line. At a development time of two minutes, however, a definite straight portion has appeared and persists for the longer times of development. Sensitometric prints and strips made on this group of papers were, therefore, developed for three minutes.

In Fig. 21 is illustrated the development performance for the group composed of Nos. 25 to 30, inclusive. A somewhat similar

FIG. 21.



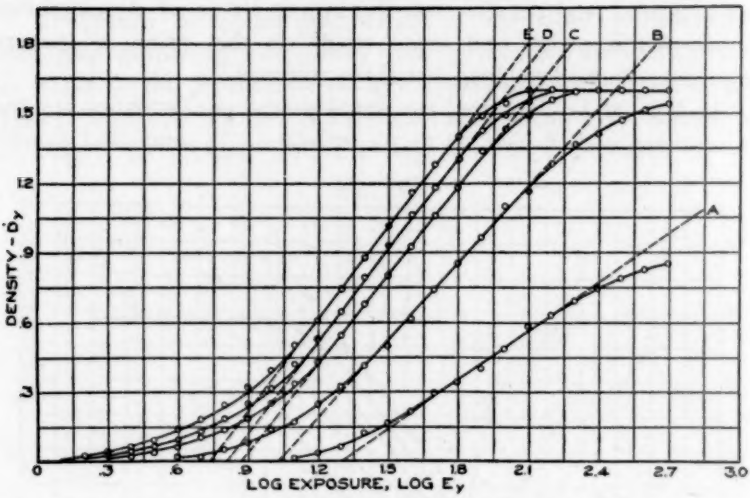
Group of sensitometric curves showing change of shape with time of development for papers of the Artura N. C. type.

effect exists, although not quite so marked as in the case represented in Fig. 20. For the development times thirty and forty-five seconds, the curves show practically no straight line portion, but for the longer periods the straight line is clearly defined. For this group of papers, also, a development time of three minutes was adopted.

For the bromide group, Nos. 33 to 37 inclusive, the curves in Fig. 22 illustrate the effect of increasing development times. In this case, there is an action similar to that occurring in the case of negative materials. Development starts comparatively slowly, and as it proceeds there is a change both in the position and gradient of the characteristic curve. For a development of one

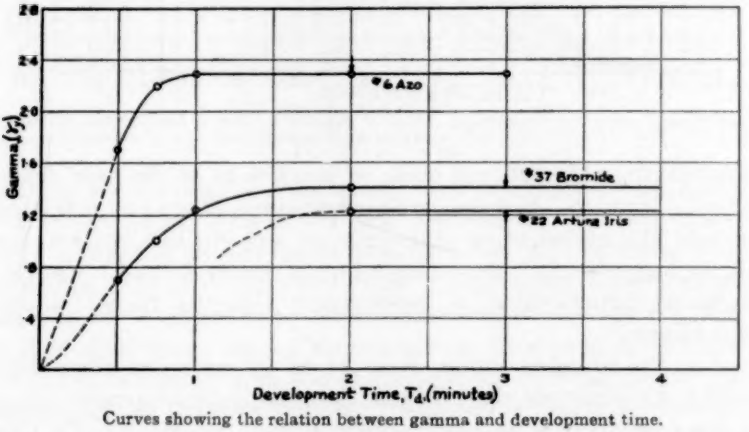
minute (curve *C*) γ has not quite attained its final value. Curves *D* and *E*, however, are identical in shape, showing that *equilibrium*, as judged from the standpoint of the shape of the curve,

FIG. 22.



Group of sensitometric curves showing change of shape with time of development for papers of the Bromide type.

FIG. 23.



Curves showing the relation between gamma and development time.

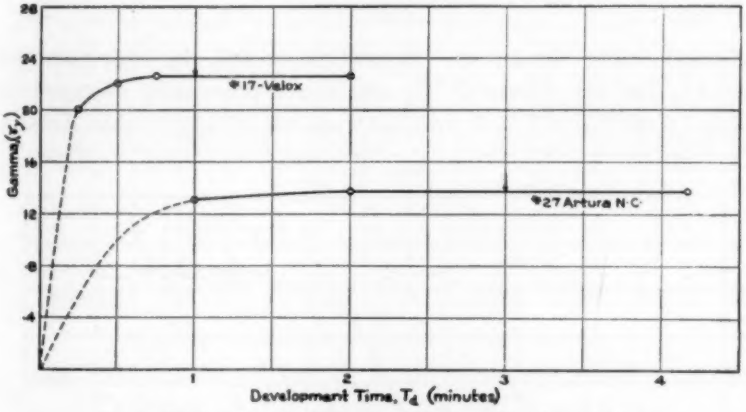
has been attained. For this group of papers a development time of three minutes was used.

The gamma values obtained with different development times

for the materials illustrated by Figs. 18 to 22 are given in Table XXIV, and from these values the curves shown in Figs. 23 and 24 are plotted. These show graphically the relation between development time (T_d) and gamma (γ_y) for the various materials as indicated. The vertical arrows are drawn in at the development times adopted for use in this work, and it should be noted that in all cases these lie at points on the $\gamma - T_d$ curves where they are parallel to the x-axis, thus indicating that development was, in all cases, carried to the point where no change of gradient was occurring.

In the data which have just been given relative to the effect

FIG. 24.



Curves showing the relation between gamma and development time.

of development time upon the shape of the characteristic curve, no times of development sufficiently long to produce any perceptible development fog were used. It should be kept in mind that the development time must not be prolonged indefinitely since, if this is increased unduly, development fog will begin to appear and the shape of the characteristic curve again changes. This is illustrated by the curves shown in Fig. 25, which represents the characteristic curves obtained with development times varying from ten seconds in the case of curve *A*, to twelve minutes in the case of curve *G*. The gamma values obtained from each of the curves are shown in Table XXV. A slightly different method of measuring the density was adopted in this particular case in order to show more clearly the growth of development fog. An

unexposed portion of the sensitive material was fixed out without development, and this was used as the standard ($D = 0$) in terms of which all density values, on the strips developed for the times

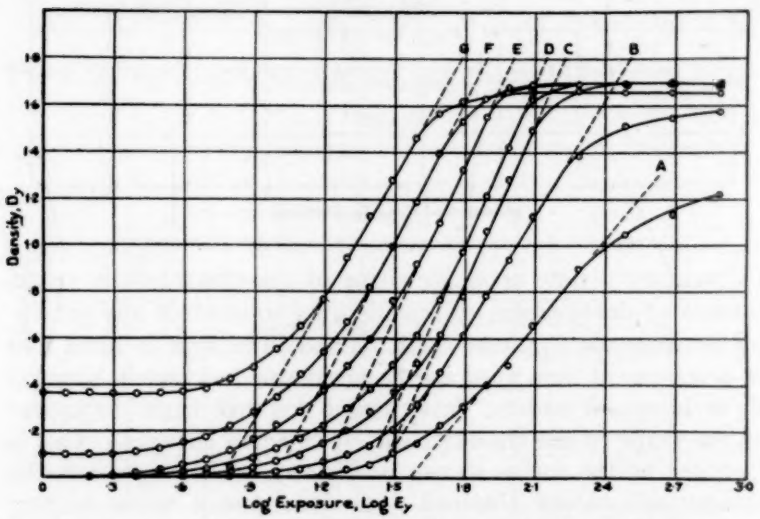
TABLE XXV.

Dependence of Gamma and Fog on Time of Development Where Development Is Continued for Extremely Long Times.

Curve.	T_d.	γ_y.	Dev. Fog.
A	10 sec.	1.24	.00
B	20 sec.	1.68	.00
C	30 sec.	2.25	.00
D	45 sec.	2.30	.00
E	2 min.	2.30	.00
F	6 min.	2.00	.10
G	12 min.	1.56	.36

indicated, were measured. It will be noted, by reference to Fig. 25, that the curves *C*, *D*, and *E* are practically identical in shape. Curve *F* ($T_d = 6$ minutes) shows an appreciable density

FIG. 25.



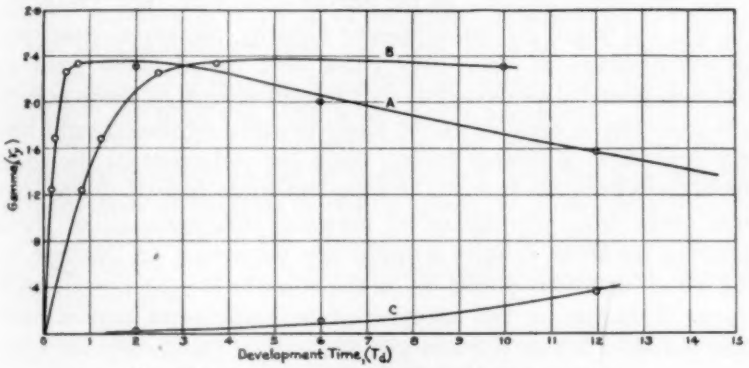
Curves showing the change in shape of the density-log *E* function when development time is prolonged sufficiently to produce appreciable fog.

due to development fog. This is manifest in the figure by the increase in the density values at the extremely low exposure end of the scale. This growth of development fog tends to cause

a decrease in the slope of the straight line portion, and when the development time is extended to twelve minutes the development fog has increased greatly and the gamma value has decreased to 1.56. It will be noted, also, that the maximum density in the case of the longest development has decreased, which may be attributable to a solvent action of the developing solution on the silver deposit.

In Fig. 26 the curves show the relation between time of development and gamma. Curve *A* shows this relationship for the entire range of development times used and indicates that

FIG. 26.



Curve showing dependence of gamma on development time.

gamma begins to decrease at about three minutes. Curve *C* shows the increase of development fog and it will be noted that this value begins to become of measurable magnitude at approximately the same development time, *i.e.*, three minutes. The curve *B* is plotted with an expanded development-time scale in order to show more clearly the relationship for the shorter times of development, which are of practical importance. The T_d values for the curve are 1/5 of the values indicated by the time scale at the bottom of the chart. It is evident from the data which have been presented in this section that there is definite range of development times over which the contrast (since contrast must be some function of the *shape* of the characteristic curve) is constant. For shorter or longer development times the contrast must vary, hence in specifying the contrast of these materials it is essential that the extent to which they are developed be definitely stated.

Various statements have appeared in the literature of photography within the last few years relative to the shape of the characteristic curve of positive materials. It has been frequently stated that in the case of these materials no portion of the curve is a straight line. The author would like to emphasize the fact that the experimental work done in this laboratory over a period of some ten years, including thousands of tests, leads to a positive conclusion that practically all of the developing-out papers give characteristic curves, which for an appreciable proportion of the exposure scale covered, depart from a straight line by amounts *much less than the experimental uncertainty* in the determination of the individual points. In the curves shown in Figs. 18 to 22, and 25, the small circles represent actually measured densities. An examination of these will show that the straight lines as drawn in many cases pass directly through several of these points. It is true that in some cases the exact position of the straight line may depend, to a certain extent, upon the judgment of the individual by whom the curve is drawn, but there is little doubt that quite aside from this factor of personal judgment, all of these materials do show definite straight line portions. In the case of Fig. 18 at least four points lie on the straight line portion of each curve. However, a few samples of developing-out papers have been tested in which the straight line region practically vanishes and is replaced by an inflection point between two inversely curved portions. This, however, is the exception rather than the rule. The author does not wish to imply, by this argument for the existence of the straight line portion, that its slope or the intersection of its intersection with the log exposure axis has anything like so great a significance in specifying the characteristics of developing-out papers as have the same values in the case of negative materials. While in the theoretical mathematical treatment of these density-exposure functions it may be difficult or impossible to account for the existence of a mathematically precise straight line region, there is no doubt, from the experimental and practical standpoint, that in the great majority of cases the departure from a linear relationship between density and log exposure (for an appreciable portion of the density scale) is less than the experimental errors involved.

The development times chosen for use in this work are considerably longer than those usually employed in practice. It is

probable that the extent to which development is usually carried is entirely satisfactory for practical purposes, but in the case of work of this kind where precise duplication of results is desired, it is advantageous to develop the paper to that point where the change occurring is small, in order that errors in the timing of development shall produce a minimum of uncertainty in the results. Furthermore, the density readings made on strips which have been developed for relatively short times show a much greater tendency to deviate from the mean value, and hence the probable error in establishing the shape and positions of the curve is much reduced for the longer times of development. In the case of reactions proceeding at such high velocities as is the case in the development of these materials, it is to be expected that local conditions will materially affect the uniformity of the results when the development time is relatively short.

The final conclusion drawn from this section relative to the development which should be used in any work dealing with the measurement of contrast is that it should be sufficiently great to insure equilibrium in the *shape* of the characteristic curve, but not sufficiently long to result in the appearance of any measurable development fog.

III. CONSTANTS DETERMINED FROM THE SENSITOMETRIC CURVES OF THE POSITIVE MATERIALS.

In the previous communication [1] certain recommendations were made for the specification of the characteristics of a printing paper in terms of a series of numbers read or computed from the characteristic curve. Since that time, the application of sensitometric results to problems of *tone reproduction* and *contrast* have led to the necessity of a more detailed analysis of the characteristic curve. The method of obtaining the first derivative of the characteristic curve and its utility was also mentioned (*loc. cit.*). Recent work has emphasized the great usefulness of this curve in obtaining certain types of information with greater facility than by use of the characteristic curve itself. The author feels that every characteristic curve should be accompanied by its first derivative if the greatest amount of information is to be conveyed. To illustrate the method of obtaining the desired sensitometric values, reference is made to Fig. 27. The small circles represent the density values obtained by averaging the readings from the

five sensitometric strips for paper No. 12. The smooth curve A drawn through these points represents the most probable relation between density and log exposure for this particular paper. The gradient, G_y, of this curve at any point, is given by the expression $\frac{dD}{d \log E}$. If now the gradient of the curve A be determined at various values of log E, it is possible to construct the curve B, which then becomes the first derivative of curve A. In plotting this first derivative it has been found convenient to use a different scale of gradient than has been adopted for density. The scale of gradient is shown at the left-hand end of the figure as indicated.

Now by drawing vertical lines through the points on the curve B where $G_y = .2$, the points a, b, on curve A are located, these being the points on the density-exposure characteristic where the gradient is equal to .2. The points c and d on the curve A are located by drawing perpendiculars through the extremities of the horizontal portion of the derivative curve D. These points lie at the extremities of the straight line portion of the characteristic curve and represent the limits of the region of maximum and constant gradient. The straight line portion of the characteristic curve extended to the log E axis forms the angle α. A straight line drawn through the points a and b makes with the log E axis the angle β. Tangent α defines the gradient of the straight line portion and is designated by the symbol γ. Tangent β defines the gradient of the line through ab, which represents the mean gradient of the characteristic curve between the points a and b and is designated by the symbol ϕ.

These curves constitute a complete description of the quality of the paper, and it is doubtful whether any series of numerical values derived therefrom can as completely represent this quality as do the curves themselves. It is essential, however, for certain purposes, to express as completely as possible this information in numerical terms. The method which has been found most satisfactory, and freest from ambiguity, is to read directly from the characteristic curve the coördinate values (D and log E) of the four points a, b, c, and d, which may be termed the *critical points* of the characteristic curve. The coördinate at each of the points is designated by the attachment, as a subscript, of the letter designating the points; thus D_a indicates the density value of the

TABLE XXVI.

Coördinates of the Four Critical Points of the Characteristic Curves for Each of the Developing-out Papers.

No.	D_y (max.).	Point *a*.		Point *b*.		Point *c*.		Point *d*.	
		D.	Log *E*.	*D*.	Log *E*.	*D*.	Log *E*.	*D*.	Log *E*.
1	1.15	.04	.82	1.11	2.67	.23	1.27	.75	1.90
2	1.19	.06	.69	1.18	2.43	.42	1.44	1.00	2.06
3	1.22	.04	.57	1.21	1.77	.41	1.13	.97	1.40
4	1.40	.05	.57	1.39	2.36	.39	1.29	1.26	2.06
5	1.40	.03	.51	1.39	2.20	.65	1.47	1.20	1.87
6	1.48	.05	1.07	1.47	2.50	.61	1.97	1.32	2.38
7	1.41	.03	.59	1.40	1.88	.47	1.25	1.10	1.49
8	1.52	.04	.37	1.51	2.24	.61	1.40	1.36	1.96
9	1.60	.07	.67	1.59	2.28	.62	1.54	1.35	1.93
10	1.67	.05	.76	1.66	2.30	.64	1.72	1.47	2.07
11	1.70	.03	.67	1.70	2.03	.55	1.37	1.30	1.61
12	1.66	.04	.43	1.65	2.00	.62	1.25	1.36	1.65
13	1.70	.03	.62	1.68	2.06	.51	1.27	1.25	1.51
14	1.23	.04	.74	1.22	2.25	.46	1.47	.95	1.82
15	1.21	.03	.68	1.20	2.00	.35	1.22	.90	1.55
16	1.50	.02	.45	1.48	2.16	.62	1.40	1.17	1.69
17	1.40	.02	.73	1.39	1.97	.67	1.46	1.10	1.65
18	1.55	.03	.50	1.54	1.88	.46	1.20	1.36	1.60
19	1.55	.02	.80	1.54	1.92	.58	1.42	1.37	1.72
20	1.16	.03	.33	1.15	1.78	.33	.91	.98	1.46
21	1.52	.02	.44	1.51	1.37	.48	.96	1.38	1.24
22	1.50	.03	.62	1.48	2.21	.44	1.30	1.39	2.07
23	1.21	.05	.63	1.20	2.28	.28	1.12	1.01	1.90
24	1.22	.04	.58	1.21	2.26	.46	1.30	1.01	1.90
25	1.23	.05	.89	1.22	2.49	.60	1.86	1.13	2.33
26	1.14	.02	.37	1.12	1.98	.33	.95	.86	1.50
27	1.47	.05	.43	1.45	1.87	.46	1.03	1.27	1.62
28	1.52	.05	.53	1.51	2.09	.60	1.38	1.25	1.77
29	1.55	.05	.58	1.54	1.91	.61	1.39	1.37	1.69
30	1.28	.05	.35	1.25	2.15	.48	1.15	1.02	1.68
31	1.36	.04	.50	1.34	2.24	.53	1.34	1.08	1.81
32	1.40	.05	.60	1.38	2.28	.42	1.30	1.18	1.92
33	1.16	.05	.48	1.14	2.20	.30	1.07	1.01	1.90
34	1.52	.05	.59	1.51	2.32	.57	1.42	1.37	2.09
35	1.28	.05	.60	1.25	2.43	.45	1.46	1.03	1.97
36	1.57	.06	.40	1.55	2.01	.58	1.20	1.33	1.73
37	1.19	.04	.50	1.16	2.16	.30	1.02	.91	1.64

point a, while log E_a indicates the log exposure value of that point, etc. In addition to the density and exposure values of the four critical points, it is necessary to read directly from the curves, the value of maximum density ($D_{max.}$). In Table XXVI are tabulated, for each of the thirty-seven developing-out papers used in the statistical work, the coördinate values of the four critical points. From these it is now possible to compute all of the necessary values for describing in numerical terms the quality of the paper as represented by the characteristic curve. From the standpoint of correlating sensitometric data with the statistical data, the following constants have been found to be necessary:

D max. = Maximum density.
DS_y = Density scale of positive material.
DL_y = Density latitude of positive material.
ES_y = Exposure scale of positive material.
EL_y = Exposure latitude of positive material.
ϕ_y = Mean gradient of positive material.
γ_y = Gradient of straight line.

The way in which these values are computed from the coördinates of the four critical points is shown by the following equations:

$$EL_y = \log E_d - \log E_c.$$

$$DL_y = D_d - D_c.$$

$$\gamma_y = \frac{DL_y}{EL_y} = \frac{D_d - D_c}{\log E_d - \log E_c} = \tan \alpha.$$

$$ES_y = \log E_b - \log E_a.$$

$$DS_y = D_b - D_a.$$

$$\phi_y = \frac{DS_y}{ES_y} = \frac{D_b - D_a}{\log E_b - \log E_a} = \tan \beta.$$

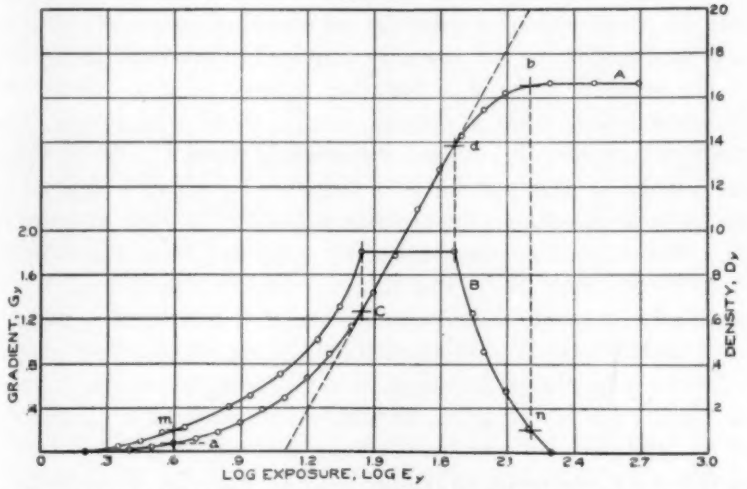
$$\frac{1}{E_a} \cdot C = \text{Speed}.$$

$$E_a \cdot 100 = E_s \text{ (Standard exposure)}.$$

It will be noted that the first three of these terms relate to the *latitude* of the material, that is to the length of the straight line portion in terms both of density and log exposure. The third, fourth, and fifth terms relate to the *scale* of the material as determined by the points a and b (Fig. 27). It should be borne in mind that the magnitudes of these values depend essentially upon the

assumption of the value of .2 as the gradient which limits the useful scale of the material. This, of course, is an arbitrary assumption, and while some of the later results will show that under certain conditions the conclusions based on this assumption are misleading, it does serve a useful purpose in expressing the values of available scale on a relative basis. The value of mean gradient (ϕ_y) appears to be of greater importance in specifying the characteristics of a paper than that of γ_y. The significance

FIG. 27.



Curve *A* is a typical density log *E* characteristic for developing-out paper. Curve *B* is the first derivative of curve *A* and shows gradient, Dd/d log *E*, plotted as a function of log *E*. The figure also demonstrates the method of locating the four critical points *a*, *b*, *c*, *d*, from the coördinates of which the numerical values of sensitometric constants may be computed.

of this value in relation to contrast will be discussed in the next section.

The value of E_a derived from log E_a is the exposure expressed in visual metre-candle seconds of a radiation of specified spectral quality required to produce the density of point *a* (Fig. 27), which lies at the point on the characteristic curve where the gradient is .2. This value is probably the most logical one to choose if it is desired to specify *speed*. It should be borne in mind that the exposure required to produce this density depends vitally upon the extent of development. This is forcibly illustrated by the curve in Figs. 18 to 22, and 25, which show that there is a marked lateral displacement of the $D - \log E$ character-

istic with respect to the log E scale (and hence a displacement of the point where $\frac{dD}{d \log E} = .2$) even after the curve has attained *shape equilibrium*. The specification of the speed or sensitivity of photographic paper, therefore, must include a rigid definition of the extent of development as well as of the quality (spectral distribution) of the light source used in making the exposure. Without a precise statement of these factors any value of *speed* is practically useless.

In the previous communication (*loc. cit.*) it was recommended that the sensitivity of a paper be expressed in terms of *standard exposure*, this being the exposure required to produce the density of the point *a* through a negative density of 2.0. Since the transmission of such a density is .01, it is evident that this *standard exposure*, E_s, is just one hundred times E_a. If we know the density of that portion of a negative which it is desired to render by a density on the positive equivalent to that of point *a*, the exposure required can be directly computed from the value of E_a. These values of E_a and E_s are inversely proportional to the sensitivity or speed of the material, and if it is desired to express this characteristic of positive materials by numbers whose magnitudes are proportional to speeds, it is necessary to use the reciprocal form. *Speed*, therefore, should be expressed as the reciprocal of E_a multiplied by some convenient arbitrary constant. It will be noted by reference to Table XXVII that the values of E_a for the papers used in this work are tabulated in the last column. These vary from .5 for the fast bromides to 1500 for the slow gaslight papers, a range of practically 1 to 3000. If all developing-out papers are to be expressed by numbers greater than unity on the same scale of speed, it would seem that a constant, $C = 10{,}000$, would produce the most convenient series of values from the practical standpoint. On this assumption the speed of the fastest bromide paper would be given by 20,000, while that of the slowest gaslight paper would be 6.7.

In Table XXVII are tabulated the sensitometric constants for the papers used in this work as computed by the foregoing formula. All of these, with the exception of D max., it will be noted, are derived from the values of the four critical points from Table XXVI. This method of obtaining the desired values

TABLE XXVII.

Numerical Values of the Sensitometric Constants Computed from the Data of Table XXVI.

No.	D_y(max.).	Scale.			Latitude.			Exposure.
		DS_y.	ES_y.	ϕ_y.	DL_y.	EL_y.	λ_y.	E_a(cm.).
1	1.15	1.07	1.85	.58	.52	.63	.83	350
2	1.19	1.12	1.74	.64	.58	.62	.94	870
3	1.22	1.17	1.20	.97	.56	.27	2.07	1540
4	1.40	1.34	1.79	.75	.87	.77	1.13	270
5	1.40	1.36	1.69	.80	.55	.40	1.37	410
6	1.48	1.42	1.43	.99	.71	.31	2.29	625
7	1.41	1.37	1.29	1.06	.63	.24	2.62	970
8	1.52	1.47	1.87	.83	.75	.56	1.34	300
9	1.60	1.52	1.61	.95	.73	.39	1.87	750
10	1.67	1.61	1.54	1.05	.83	.35	2.37	860
11	1.70	1.67	1.36	1.23	.75	.24	3.12	1260
12	1.66	1.61	1.57	1.03	.74	.40	1.85	550
13	1.70	1.65	1.44	1.15	.74	.24	3.08	1470
14	1.23	1.18	1.51	.78	.49	.35	1.40	200
15	1.21	1.17	1.32	.89	.55	.33	1.67	650
16	1.50	1.46	1.71	.85	.55	.29	1.89	165
17	1.40	1.37	1.24	1.10	.43	.19	2.26	690
18	1.55	1.51	1.38	1.09	.90	.40	2.25	200
19	1.55	1.52	1.12	1.36	.79	.30	2.63	760
20	1.16	1.12	1.45	.77	.65	.55	1.18	180
21	1.52	1.49	.93	1.60	.90	.28	3.21	1100
22	1.50	1.45	1.59	.91	.95	.77	1.23	1330
23	1.21	1.15	1.65	.70	.73	.78	.94	1200
24	1.22	1.17	1.68	.70	.55	.60	.92	1050
25	1.23	1.17	1.60	.73	.53	.47	1.13	1020
26	1.14	1.10	1.61	.68	.53	.54	.98	600
27	1.47	1.40	1.44	.97	.81	.59	1.37	800
28	1.52	1.46	1.56	.94	.65	.39	1.66	1000
29	1.55	1.49	1.33	1.12	.76	.30	2.53	2300
30	1.28	1.20	1.85	.65	.54	.53	1.01	15
31	1.36	1.30	1.74	.75	.55	.47	1.17	25
32	1.40	1.33	1.68	.79	.76	.62	1.22	30
33	1.16	1.09	1.72	.63	.71	.83	.86	0.70
34	1.52	1.46	1.73	.84	.80	.67	1.19	0.95
35	1.28	1.20	1.83	.66	.58	.51	1.14	0.50
36	1.57	1.49	1.61	.93	.75	.53	1.41	1.25
37	1.19	1.12	1.66	.67	.61	.62	.98	0.95

has proved to be most satisfactory, since it gives a fairly complete and direct analysis of the characteristic curve in terms of numerical constants.

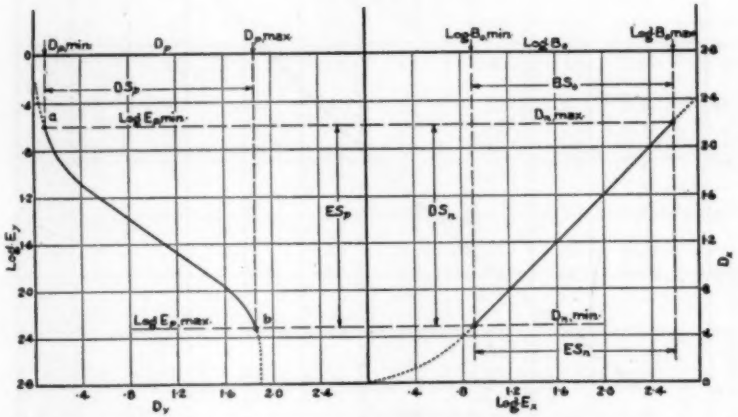
It is interesting to note that the value of density scale, DS_y, may be obtained with satisfactory precision by subtracting a constant from the value of D_y max. It will be seen by referring to Table XXVI that the values of D_a (third column) are fairly constant, which means that the point where $\frac{dD}{d \log E} = .2$ occurs at about the same density for all of these papers. The mean of D_a is .04 and the mean deviation from this value for the entire group is .007. Further, if the difference between D max. and D_b be determined for each paper it will be found that this also varies but little, the mean value being .02. It is evident that $DS_y = D_y$ max. $- (D_y \text{ max.} - D_b + D_a)$. The mean value of the parenthesis in the second member of the above equation was found to be .06 for this group of papers, and hence we may write $DS_y = D_y$ max. $- .06$. In order to test the amount of error introduced by this method of finding density scale, the equation was applied to each of the papers, and it was found that the mean deviation was only .01. Since the mean value, DS_y, for the entire group is 1.35, it follows that the mean deviation expressed as a percentage is only 0.7 per cent. The maximum deviation from the mean was only 2.0 per cent. It seems justifiable then, in case it is desirable, to determine DS_y in this way, thus eliminating the necessity of locating the points where the gradient of the characteristic curve becomes equal to .2. The location of point a at $D = .04$ and of the point b at $D = D_y$ max. $- .02$ may also be resorted to without the introduction of any serious errors in the locations of these points. It is also of interest to note that if the entire characteristic curve of a paper between the points a and b is utilized that only .06 of the available maximum density scale is sacrificed.

The final results derived from sensitometric work are the values contained in Table XXVII. The correlation of these with those resulting from the statistical study (Table XVIII) and the development of a method for computing contrast by combining the statistical and sensitometric results will constitute the subject-matter of the later sections.

IV. DETERMINATION OF COLOR COEFFICIENT (χ).

It will be recalled that the negatives used in the statistical work, of which an account has already been given in section *B*, were made by using a pyro developer which produced a perceptibly yellow image. The values of negative density measured by the usual visual method are, therefore, not true values of effective photographic density, since, as a result of selective absorption, such silver deposits possess a somewhat greater opacity for the light to which the positive materials are sensitive than is indicated by the visual values. The ratio of photographic to visual density in

FIG. 28.



Partial tone-reproduction diagram illustrating the equality of the negative density scale, DS_n, and positive exposure scale, ES_p, when both are expressed in photographic units.

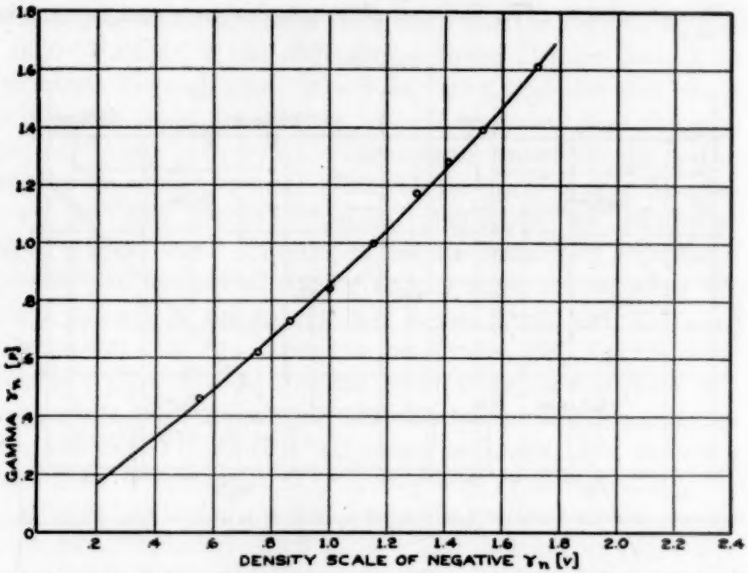
such cases is referred to as the color coefficient and is represented by the symbol χ. Direct sensitometric measurements were made to determine the magnitude of this value. Various types of positive materials used in making prints were used in this work, and while a slight variation for the different materials was found, this was not great and a mean value of 1.20 was considered as representing with sufficient precision the entire group of materials.

The characteristic curves of the various printing papers, and the maximum and minimum density values for the optimal prints now being available, it is possible to make an independent check upon the value of χ, and since in work of this kind every advantage must be taken of checking and counter-checking the results,

in order to be certain of consistency throughout, the evaluation of χ by this second method will be discussed.

Referring to the partial tone-reproduction diagram shown in Fig. 28, it will be seen that the exposure scale of the positive, ES_p, must be equal to the density scale of the negative, DS_n, from which the positive was made. This is true only when the density scale of the negative is expressed in terms of density (photographic density, $D_n(p)$) as measured by the positive

FIG. 29.



Curve showing negative gamma (in photographic units) as a function of negative density scale (in visual units). This is used as an interpolation scale for finding the values of visual density scale for the optimal negatives.

material on which the print is made. Now for each positive material it is possible to lay off on the characteristic curve the positions of the maximum and minimum optimal print densities as indicated by the letters b and a (Fig. 28), respectively. Horizontal lines drawn through these points to the scale of log E now determine the magnitude of the exposure scale of the print, ES_p, and it is evident from the diagram that this must be equal to $DS_n(p)$. All density measurements on the negatives, as well as sensitometric strips made on a negative material, were made by a visual method, and hence the values of density scale deter-

mined directly from such measurements are not in terms of photographic density. From the values shown in Table VI, it is possible to plot a curve (Fig. 29), showing the relation between $DS_n(v)$ and $\gamma_n(p)$. Now by taking the γ values for the optimal negatives as shown in Table XVIII, it is possible to determine the visual density scale for each of the optimal negatives. These

TABLE XXVIII.

Values Used in the Computation of the Color Coefficient (χ). These Values Are Derived Directly from the Optimal Negatives and Optimal Positives and Hence Give a Value of Color Coefficient as Determined Independently of the Sensitometric Measurements.

No.	ES_p.	$DS_n(u)$.	χ.	$\Delta\chi$.	No.	ES_p.	$DS_n(u)$.	χ.	$\Delta\chi$.
1	1.77	1.48	1.20	−.02	20	1.28	1.11	1.15	−.07
2	1.51	1.28	1.18	−.04					
3	.83	.69	1.20	−.02	21	.58	.49	1.18	−.04
4	1.64	1.33	1.23	+.01	22	1.35	1.17	1.15	−.07
5	1.40	1.15	1.22	0	23	1.49	1.27	1.17	−.05
6	.99	.84	1.18	−.04	24	1.53	1.27	1.20	−.02
7	.82	.65	1.26	+.04	25	1.38	1.18	1.17	−.05
8	1.70	1.39	1.22	0	26	1.46	1.26	1.16	−.06
9	1.36	1.09	1.25	+.03					
10	.96	.79	1.21	−.01	27	1.25	.98	1.22	0
11	.73	.57	1.28	+.06	28	1.15	.93	1.24	+.02
					29	.86	.65	1.32	+.10
12	1.14	.97	1.18	−.04					
13	.72	.56	1.28	+.06	30	1.49	1.23	1.29	+.07
					31	1.42	1.19	1.19	−.03
14	1.33	1.07	1.24	+.02	32	1.40	1.17	1.20	−.02
15	.95	.77	1.23	+.01					
					33	1.72	1.41	1.22	0
16	1.29	1.06	1.22	0	34	1.45	1.25	1.16	−.06
17	.89	.72	1.24	+.02	35	1.74	1.39	1.25	+.03
					36	1.34	1.08	1.24	+.02
18	1.01	.85	1.19	−.03	37	1.49	1.27	1.17	−.05
19	.73	.57	1.28	+.06					
					Mean		1.22		.034
									2.7%

are shown in the columns designated as $DS_n(v)$ (Table XXVIII), while in the columns designated as ES_p are the exposure scales for the various optimal prints, as determined directly by laying off the maximum and minimum print densities on the characteristic curves. It is evident, since from tone reproduction requirements ES_p must be equal to $DS_n(p)$, that

$$\chi = \frac{ES_p}{DS_n(v)}.$$

The values of x obtained thus are shown in Table XXVIII and the mean for the entire group is seen to be 1.22. This checks remarkably well with the values obtained by the direct sensitometric method. In fact, the agreement is better than can usually be expected in this type of work. In the column (Table XXVIII) designated as Δx are the deviations of the individual readings from the mean, and at the bottom of the right-hand portion of the table the mean deviation is computed and shown to be 2.7 per cent.

The possibility of determining color coefficient in this way rests upon one assumption which should be recognized. The density scale of the negative from which the print is made must not be so great that the maximum and minimum negative densities are rendered at points on the characteristic curve of the positive material where the gradient is zero. In all cases of the optimal negatives and positives used in this determination these limiting points were well within the portions of the characteristic curve where the gradient had a value appreciably greater than zero. It is felt that this method of determining color coefficient, based as it is upon a much larger number of values than were afforded by the sensitometric one, gives the most reliable result and hence the value of 1.22 has been used throughout for converting from visual to photographic density values.

It may be well at this time to summarize what has thus far been accomplished and to indicate briefly the nature of the treatment of the experimental data to be given in the following section. In the second section (Section *B*) a statistical method of determining the quality of negative best suited for use with different developing-out papers was discussed in detail. As a result of this work numerical values for the characteristics of these optimal negatives, and the optimal prints resulting therefrom, were obtained. In this section (Section *C*) the sensitometric characteristics of the various developing-out papers have been determined and expressed in the form of numerical values. It now remains to correlate the results obtained by the statistical and sensitometric methods. Using the values applying to the optimal negatives and positives, it will be possible to determine just what portion of the total available characteristic curve of the positive material was used in the production of the optimal

positives and by the proper evaluation of the sensitometric characteristics of these usable portions, values of useful or effective contrast can be computed. This work of correlation and computation of contrast will form the subject-matter of the next section.

SUMMARY.

The results obtained in Section *C* may be summarized as follows:

(*a*) A careful analysis of the errors involved in the sensitometry of positive materials has been made from which it is concluded that the *reading error* is of greatest magnitude. The total error, however, is small, and a characteristic curve based upon the average of five sensitometric strips should not be subject to a density error of more than ± .015.

(*b*) The effect of development time upon the characteristic curve of the positive material is discussed. It is shown for these, with the exception of the bromide papers, that the development is very rapid. Maximum density and maximum gradient are obtained in a relatively short time, after which further prolongation of development produces no change in the *shape* of the characteristic curve, but does produce a lateral shift of the entire curve. From the standpoint of contrast, therefore, an equilibrium is reached after a relatively short time of development. It is pointed out that the *contrast* of a material must depend upon time of development unless development is carried to such an extent that equilibrium in the shape of the curve is reached.

(*c*) Results of the sensitometric examination of each of the thirty-seven positive materials used are given. It is shown that from the coördinate values of four critical points all of the necessary sensitometric constants, with the exception of *D* max., can be computed. This method gives some additional sensitometric constants and results in a more complete expression in numerical terms of the characteristics of the material as expressed by the density-log exposure function.

(*d*) Using the sensitometric curve for each material and the values of maximum and minimum density for the optimal prints, the color coefficient of the negatives is computed. This method gives a value in very close agreement with direct determinations of color coefficient by strictly sensitometric methods.

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(To Be Continued.)

The 27-Day Recurrency in Earth Currents. W. J. PETERS and C. C. ENNIS. (*Terrestrial Mag. Atmospheric Elec.*, June, 1926.)—By the investigations of Chree and others it is known that average high and average low values of magnetic quantities, such as international character numbers and daily ranges recur on the twenty-seventh day after days of maximum or minimum values picked out from unbroken records. Moreover, Bauer has shown a high correlation between magnetic variations, atmospheric electricity and earth-currents. It is, therefore, to be expected that in the case of earth-

currents there will be a recurrence of high or low values after twenty-seven days. Accordingly a study has been made of the observations on earth-currents recorded at the Ebro Observatory, Spain, from 1910 to 1924. While it is not true that all the highest and all the lowest values in the daily range of earth-currents are inevitably followed twenty-seven days later by high and low values, respectively, though this often happens, yet "the investigation has shown that the high and low values that follow, fall on and around the twenty-seventh day in such a way that the mean value for a number of years on the twenty-seventh day after the highest value is a high value and the mean value on the twenty-seventh day after the lowest value is a low value." A similar recurrence is certainly true also for the fifty-fourth day and perhaps for the eighty-first as well, though to a less striking extent.

It may be that the interval of twenty-seven days is connected with the period of rotation of the sun. G. F. S.

The Michelson-Morley-Miller Experiment Carried Out in a Free Balloon. A. PICCARD and E. STAHEL. (*Comptes Rendus*, Aug. 17, 1926.)—Since Dayton Miller's announcement to the A.A.A.S. last December that his experiments on Mount Wilson seemed to show a drift of the ether, definite though small, there is renewed interest in this experiment devised by Michelson and commonly regarded as the foundation of Einstein's Theory of Relativity. The University of Brussels has undertaken to repeat the measurements on a free balloon. The first attempt was made on the night of June 20, 1926, on the balloon *Helvetia*, containing 2200 cubic m. of hydrogen. The Michelson interferometer with an optical path of 280 cm. in each branch was in a space supposed to be kept at constant temperature. The mercury line, 4538 Å., was used. By electric motors the balloon was made to rotate two or three times a minute. In all there were satisfactory observations recorded photographically during 96 rotations, the elevations being 2500 m. Later another series of observations was made by eye at a height of 4500 m. In neither case were the investigators able to detect a flow of the ether past the balloon. "However, our limit of precision is not sufficiently low to confirm or to confute the measurements made by Miller on Mount Wilson. We can only say that, if his ether drift exists, it did not increase with the altitude at the time and place of our observations, as it should have done because the observers were removed from the surface of the earth." It is significant that it is stated that the failure of the thermostat to work reduced the accuracy of the observations. The value of this investigation lies not in the results it has already obtained, but much more in the possibility it presents of repeating this highly important experiment away from the surface of the earth and from its material entanglements. G. F. S.

A PROBLEM IN UNDER-WATER ACOUSTICS.

BY

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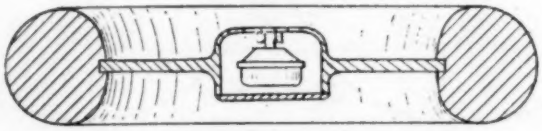
THE ready passage of sound through water enables a listener to hear ships at a considerable distance. To Leonardo da Vinci is credited the expedient of listening to under-water sounds by placing an ear to the end of an oar, the blade of which is under water. A piece of rubber tubing with one end blocked, and the other

FIG. 1.



Bidirectional hydrophone.

applied to the ear, is also an excellent device, if the tube is filled with air and sunk for a few feet beneath the water.

Far more efficient hydrophones have been made by placing ordinary carbon telephone transmitters inside an air-filled metal disc sunk a few feet beneath the water at the end of a rod. Connecting wires from the transmitter are led to an ordinary headpiece as used in radio, and, of course, a battery of about six volts is placed in series. A great increase in efficiency is obtained by employing an amplifying set of about three electron valves.

During the war a hydrophone was evolved from the initial form where the microphone was placed in a large metal case to a later variety where the microphone was enclosed in a small case which was fixed at the centre of a bronze disc surrounded by a heavy ring (Fig. 1). The latter instrument had directional properties with a "figure-of-eight" diagram (Fig. 2). When "edge on" to a source of sound under water the instrument gave to the listener comparative silence, but when either face of the disc was directed to the source a maximum sound was obtained. It was obviously uncertain, therefore, to the observer whether the source was in one or other of two opposite directions.

This difficulty was overcome by placing a screen or baffle plate

parallel to the metal disc, at a few centimetres distance from it (Figs. 3 and 4). Such a baffle plate required much investigation in order to obtain a good oval in place of the above-named figure-of-eight (Fig. 5). If the baffle plate were made of solid metal,

FIG. 2.

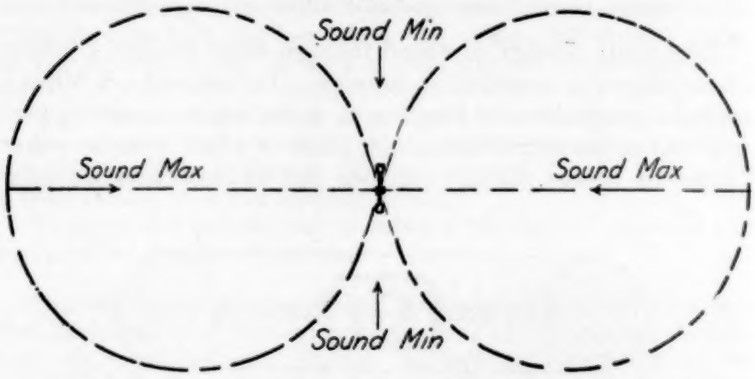
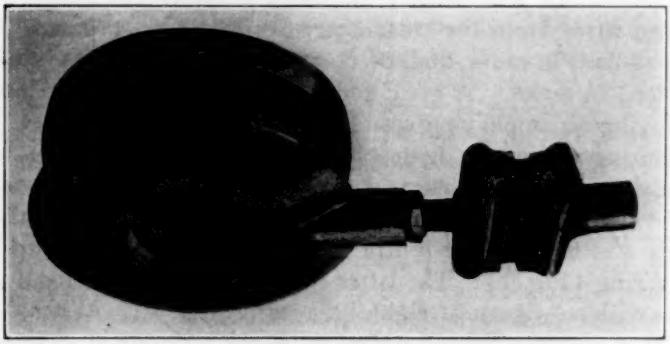


Figure of eight for bidirectional hydrophone; two maxima and two minima.

the hydrophone would be practically unaffected by its presence, because the sound would pass through the metal in almost the same manner as through water. On the other hand, a hollow

FIG. 3.



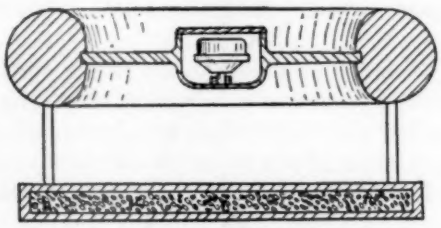
Hydrophone with baffle, bidirectional.

metal case, containing air, would reflect sound from both sides, and the loss by reflection from one side would nearly compensate for the gain due to reflection from the other side.

The first type of successful baffle was a disc of dry wood cov-

ered with lead. As soon as the first specimens, hand-made, were found to be satisfactory, production in quantity was begun. Surprise and disappointment were experienced when it was found that these machine-made baffles were complete failures. In the meantime, Mr. F. L. Hopwood had also made other baffles of brass or of celluloid containing lead shot almost filling an air cavity but sufficiently loose just to rattle to and fro, or up and down. These baffles seemed capable of reproduction in large numbers without difficulty. There is, not far from Harwich, a celluloid factory, where there was on hand a large quantity of well-

FIG. 4.



Section of hydrophone and baffle.

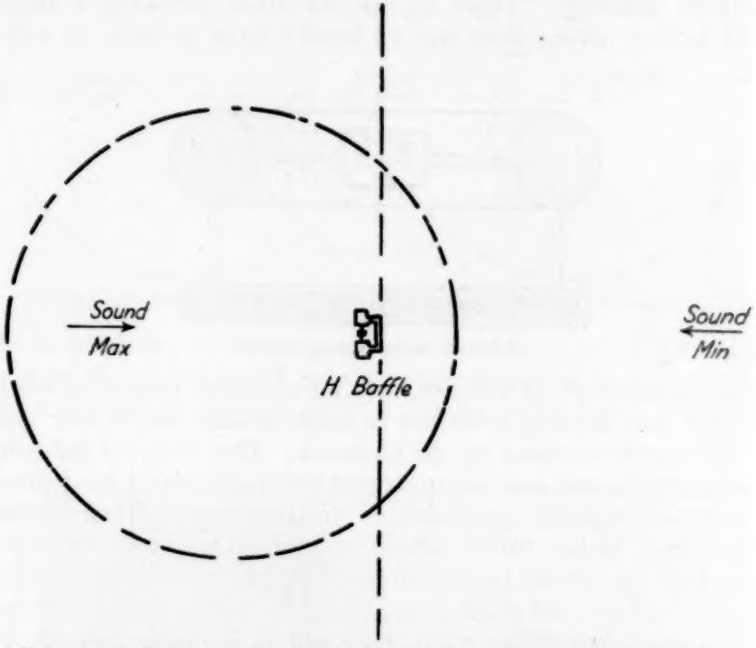
seasoned celluloid, or xylonite, held for a French factory of knife handles, but delivery could not be made because the factory was in the region occupied by the Germans. This stock of celluloid was available and was manufactured into baffle plates for hydrophones either used overboard on trawlers, or enclosed within fish-shaped bodies towed behind submarine hunters. In some apparatus there were two controlled hydrophones, rotated step by step. One was unbaffled, giving quickly the figure-of-eight, so that a submarine source could be located as, let us say, 40° E. of N. or 40° W. of S., and then a switch-over could be rapidly made to the baffled hydrophone so as to settle which of these two directions was actually that of the under-water source.

Manufacture and testing proceeded satisfactorily for some months, and then a curious thing happened. A batch of newly made baffles was found to be valueless! On inquiry it was discovered that the only change made was in the supply of lead shot. The new shot were far from uniform in size. Some baffles which failed were therefore opened, the variable shot were removed, uniform shot were substituted, and the excellent properties of the baffle were immediately regained. On procuring a fresh supply

of good shot the baffles were turned out as desired until the end of the war. It may be noted, however, that unseasoned celluloid, with a tendency to warp, was never satisfactory.

Although the practical problem was solved, it was always felt by those concerned that better results could be obtained if the principles involved were understood. For example, why were the hand-made wood-lead baffles often successful and the machine-

FIG. 5.



Hydrophone with baffle, now unidirectional with well-marked maximum and minimum.

made ones all failures? Why were celluloid-lead baffles successful with uniform shot, and unsuccessful with irregular shot? Why had each baffle to be adjusted to each hydrophone with a precision of about a centimetre so as to give good results? What factors determined this distance? It may be pointed out that every hydrophone had its individual fundamental note when struck under water.

In fine, how does a regular distribution of obstacles or apertures affect a plane wave of sound when the obstacles or apertures are small compared with the wave-length? For example,

with a frequency of sound equal to a thousand, the wave-length in water would be about 140 cm., while an individual shot in the baffle was less than half a centimetre in diameter. This is widely different from the cases of diffraction when visible light (10^{-5} cm.) passes through a pin-hole (10^{-3} cm.), or of coronas produced by light passing through lycopodium in Fraunhofer's experiment, or of diffraction rings in the eriometer of Young. In the case of the sound wave the wave-length was about 300 times as long as the obstacle was wide; in the case of light, the wave-length might be about one-hundredth part of the diameter of the aperture, or obstacle, producing diffraction. The late Lord Rayleigh frequently called attention to this disparity in his collected papers.

As those engaged in the pressing problem of production of hydrophones and baffle plates were unable to ascertain the underlying principles involved, the matter was referred to the late Lord Rayleigh, who replied that he could not hazard an opinion without a more complete knowledge of all the details involved.

The problem then remains unsolved and the object of this paper is to place the matter on record, and to invite the attention of scientific men to the question of the scattering of sound by obstacles, or aperture, small in comparison with the wave-length. For, by Babinet's principle, obstacles and apertures are equivalent in their diffraction effects.

It may not be out of place to record some points and principles which throw some light on the phenomena in question.

A description of the various hydrophones is given by Dr. C. V. Drysdale, pp. 299–301, Chapter IX, in "The Mechanical Properties of Fluids" (Blackie and Son, 1923). The illustrations have been copied from that book. In the collected works of Stokes and of Rayleigh references are made in several places to coronas. In particular, there is the beautiful experiment of Fraunhofer, who saw colored rings when looking at a candle or bright point of light through lycopodium scattered on a glass plate. The spores from a puff-ball give rings much larger than do the lycopodium spores, because the former are smaller. My colleague, Doctor Emmons, has applied this method of coronas in the investigation of the size and shape of the blood corpuscles of man, cat, rabbit, hen, and detected the marked change of size induced by pernicious anæmia in man. The coronas due to the quick expan-

sion of air and water vapor are well known. It is not, however, possible to obtain these coronas with dried milk, face powder, or with particles of *unequal* size.

It may be noted in passing that the coronas above referred to may all be projected by a lens onto a white or ground-glass screen so as to be visible to a large audience.

The fact that obstacles of uniform size in large numbers with random distribution will produce coronas, while they will not do so if their sizes differ, is suggestive of the results due to equal and unequal shot in the baffle plate referred to above.

In the case of the breath causing a film on glass, a white halo [1] is produced, due, as Rayleigh points out, to irregular lens-shaped discontinuous particles of water. A small length of the edge of each droplet acts as a prism so that the bending of the rays and therefore the size of the white halo is a measure of the angles which the edges of the water or mist droplets make with the glass. It is not certain if the shot in the baffles are similar in their action to the mist drops or to the lycopodium dust in producing a symmetrical scattering away from the hydrophone. But if so, why is the adjustment of distance between baffle and hydrophone so essential? And again, in the case of the wood-lead baffle, it is difficult to imagine any symmetry unless it existed in the dried wood itself, whereas the irregular cavities between the wood and the lead were generally considered the cause of the scattering of sound which appear to be the essence of a good baffle.

The following letter to *Nature*, written long ago by the late Lord Rayleigh, is so arresting in interest that it is justifiable to reproduce it in full.

HARMONIC ECHOES.[2]

According to Doctor Brewer,[3] "The harmonic echo repeats in a different tone or key the direct sound. The harmonic is generally either the third, fifth or tenth of the tonic . . . On the river Nahe, near Bergen, and not far from Coblentz, is an echo thus described by Barthius—it makes seventeen repetitions at unequal intervals. Sometimes the echo seems to approach the listener, sometimes to be retreating from him; sometimes it is very distinct, at others extremely feeble; at one time it is heard at the right, and the next at the left; now in unison with the direct sound, and presently a third, fifth, or tenth of the funda-

[1] When the film is thin and frozen on the pane, beautiful coronas may be seen, if the frost particles are approximately equal in size.

[2] *Nature*, VIII, pp. 319, 320, 1873.

[3] BREWER, "On Sound and Its Phenomena" (1864), p. 305.

mental. Occasionally it seems to combine two or more voices in harmony, but more frequently it resembles the voice of a single mimic.

"At Paisley, in Scotland, there is a somewhat similar echo in the burying-place of Lord Paisley, Marquis of Abercorn. Musical notes rise softly, swell till the several echoes have reverberated the sound either in unison or harmony, and then die away in general cadence.

"At the Lake of Killarney, in Ireland, is a very celebrated harmonic echo, which renders an excellent second to any simple air played on a bugle.

"There was formerly, according to the authority of Doctor Birch, an harmonic echo no less remarkable, seventeen miles above Glasgow, near a mansion called Rosneath. If a trumpeter played eight or ten notes, the echo would repeat them correctly a third lower. After a short silence another repetition was heard, still lower than the former; and after a similar pause the same notes were repeated a third time, in a lower key and feebler tone, but nevertheless, with the same undeviating fidelity. This echo no longer exists."

It is difficult to believe that these descriptions are accurate, but that they have a basis of truth there can be little doubt. My attention was first drawn to the subject by an echo at Bedgebury Park, the country residence of Mr. Beresford Hope. The sound of a woman's voice was returned from a plantation of firs, situated across a valley, with the pitch *raised an octave*. The phenomenon was unmistakable, although the original sound required to be loud and rather high. With a man's voice we did not succeed in obtaining the effect.

At the time I had no idea that such an alteration of pitch had ever been observed, or was possible; but it soon occurred to me that the explanation was similar to that which I had given of the blue of the sky a year or two previously (*Phil. Mag.*, Feb., 1871). Strange to say, at the very time of the observation, I had in my portfolio a mathematical investigation[4] of the problem of the disturbance of the waves of sound by obstacles which are small in all their dimensions relatively to the length of the sound-waves. In such a case (precisely as in the parallel problem for light) it appears that the reflecting, or rather diverting, power of the obstacle varies inversely as the fourth power of the wave-length. When a composite note, such as that proceeding from the human throat, impinges on the obstacle, its components are diverted in very different proportions. A group of small obstacles will return the first harmonic, or octave, sixteen times more powerfully than the fundamental. After this, it is not hard to understand how a wood, which may be considered to be made up of a great number of obstacles, many of which, in two or three of their dimensions, are small in comparison with the wave-length, returns a sound which appears to be raised an octave.

The increased reflection is, of course, at the expense of the direct sound. If we conceive a group of small obstacles to act on a train of plane waves of sound, the effect will be a diffused echo, which may be heard on all sides, appearing to proceed from the group, and the direct waves which maintain their direction. If the original sound be composite, the diffused echo contains the higher elements in excessive proportion, and for the same reason the direct wave, being shorn of these higher elements, will appear duller than the original sound.

[4] Since communicated in an amplified form to the Mathematical Society (Art. xiv).

It is well known that pure tones are liable to be estimated an octave too low, and thus it may be possible that a note in losing its harmonies may appear to fall an octave.

What is here called the direct sound may itself be converted into an echo by regular reflection. For example, if a plane wall were covered with small projections, there would be a diffused echo, due to the projections in which the higher elements preponderated, and an ordinary echo, obeying the law of reflection, in which the lower elements would preponderate.

It appears probable that Rayleigh's letter to *Nature*, published in 1873, may contain a suggestive answer to the problem of 1917. The propeller of any ship conveys to the water sounds of a great variety of pitch which may be compared with a continuous spectrum. If a group of these are deflected by the baffle away from the hydrophone, the ear would be quick to detect a change in kind as well as a change in intensity. At first sight it would appear that a number of shot in a plane would give rise to a secondary plane surface, but Rayleigh ("Theory of Sound," Chapter XV) points out that a region of altered density acts like a double source, and the energy of the secondary waves might therefore be deflected away from the metal diaphragm and from the central microphone vibrating with it. This suggestive point of view does not, however, throw light on the necessity for adjusting each baffle to an optimum distance from the hydrophone, nor on the success of the hand-made and the failure of the machine-made wood-lead baffles.

Tyndale once called attention to the fact that in *air* a piece of stiff felt half an inch thick allows much more sound to pass through than a *wetted* pocket handkerchief, which, in consequence of the closing of its pores, behaves rather as a thin lamina.

Lamb, in his "Hydrodynamics" (Articles 293, 294, fourth edition), discusses the case of waves striking an obstacle small in comparison with the wave-length. It appears that the waves are scattered from such an obstacle (1) as if from a simple source, so that a number of shot in a plane would give, on Huyghen's principle, a parallel plane wave surface as usually contemplated and expected, but also (2) in the case of an oscillating obstacle as if from a *doublet* leading to maximum scattering at *right angles* to the line of travel of the sound. With a group of obstacles this result suggests lateral scattering. There still remain many difficulties which can be solved more readily, perhaps, by experiment than by difficult mathematical operations. It will be recollected that, in Rayleigh's theory of the blueness of the sky, the scattered

waves are about a thousand times as long as the diameters of the molecules which scatter them.

Under water a lead shot is a conductor and an air cavity a reflector of sound. The exploration of under-water waves, particularly in the case of obstacles small in comparison with the wave-length, deserves further attention from those who are fortunate enough to be able to undertake it.

The Solar System—Some Unsolved Problems. R. G. AITKIN. (*Science*, Aug. 27, 1926.)—In this, the address of the retiring president of the Pacific Division of the American Association for the Advancement of Science, the arresting statement is made, "I think it no exaggeration to say that the North American Indians in the days of Columbus knew more about the apparent motions of sun, moon and planets, about the configuration of the stars, and the relation of their appearance in the night sky to the seasons of the year, than does the average university graduate to-day."

Since the emphasis of astronomical research at the present time is laid on matters more remote from us than our own solar system, it might be concluded that no problems near to the earth remain to be solved. Professor Aitkin undertakes to show that such is by no means the case.

Celestial mechanics is rightly considered one of the most exact of sciences, yet in the motion of the moon and the planets there are anomalies without explanation up to the present. Though the tables of E. W. Brown are computed from equations containing about 1500 terms, it still is true that, "There are oscillating differences (between observation and theory) which do not correspond to any theoretical gravitational terms, and they are large enough to exclude the possibility of being due to errors either in the theory or in the observations." Simon Newcomb proposed a solution of the difficulty on the basis of changes in the earth's rotation. E. W. Brown calculates that changes in the radius of the earth of from 5 inches to 12 feet might be sufficient to account for the discrepancies.

In spite of the proximity of the moon, astronomers are not unanimous in interpreting their observations to mean that no life exists on that body, and that the craters were caused by explosions similar to volcanic action rather than by external bombardment as is suggested by Ives' photographs of pits made by aerial bombs, taken from an airplane. Moreover, the bright streaks radiating from some great craters call for an explanation. Even the shape of the moon, spherical or ovoid, is not certain.

Among the planets, we have the most complete information about Mars. Seasonal color changes on the surface of this body are undis-

puted, but it is not so certain that the changes are due to the presence of vegetation. In interpreting the famous canals, astronomers are no more a unit than they were a generation ago, and with this is bound up the question of the habitability of this neighbor of the earth. Observations made at the opposition in 1924 placed in doubt conclusions previously drawn in regard to the Martian atmosphere.

The physical condition of Jupiter and Saturn is an open question, and we do not know the significance of the fluctuating and complex markings similar to belts that appear on their surfaces. Like the sun their periods of rotation vary with latitude and the reason is not surely known.

In the spectra of light from the four outermost planets, Jupiter, Saturn, Uranus, and Neptune, there are broad absorption bands in the red. These are of unknown origin. There is no plausible hypothesis accounting for the formation of the rings of Saturn. The existence of the thousand asteroids between Mars and Jupiter was formerly attributed to the shattering of a planet. This is now untenable, but no more satisfactory explanation has replaced it.

The Jupiter family of comets, whose aphelia reach to this planet while, when nearest to the sun, they lie within the orbit of Mars, is peculiar in this that its members are without tails. It remains to determine whether Jupiter attracted them into their present orbits. The origin and history of the many comets existing on the borders of the sun's domain present many additional problems for solution.

The sun contains 99 6/7 per cent. of the mass of the solar system and our intimate dependence upon it enhances the desirability of our understanding as completely as possible all about it. The cause of sun-spots, of their periodic variation and of many other curious features in their appearance and progress lack convincing explanation. The sun radiates energy at the rate of 10^{24} horsepower and has been doing this for, perhaps, a billion years. The total quantity of energy radiated in this time appals the scientific imagination. The Helmholtz-Kelvin theory accounted for the energy dispensed by the sun as due to the approach of the mass of that body toward its centre, but not sufficient energy could thus be provided to equal all that has left the sun. Now it is held that the energy radiated comes from rearrangement of structure in the matter of the sun. The energy sent out by the sun in a year amounts to 12×10^{13} tons. At this rate in 15×10^{9} years the sun would lose only 1/1000 of its mass. Even if this theory stand the test of criticism in coming years, there still confronts the astronomer the question of the mechanism of the release of this energy or of the method of the conversion of mass into energy.

It is wise to take stock of our ignorance. This paper may well serve as a stimulus to the solution of the questions propounded.

G. F. S.

THE DISPERSION OF X-RAYS.*

BY

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THE tremendous stimulus which the discovery of X-rays [1] and radio-activity [2] has given to the progress of the physical and other sciences, during the last three decades, is a matter of common information. Notwithstanding this, the situation which preceded the period is not so widely known. As late as in the seventies of the past century the marked successes of the older concepts and developments of dynamics, with the marvellous background of their earlier applications throughout astronomical time and space, in dealing with the phenomena of heat, sound, optics, electricity and magnetism, led eminent men to venture the opinion that the time for large advances in physics was past; to a great degree the house of physics was in order and the progress of the future would be concerned, principally, with more and more accurate evaluations of the constants characteristic of these great divisions of the subject. Clouds were not long forming upon such an horizon. During the last two decades of the nineteenth century four of the most interesting, but perplexing, discoveries in the history of science were made known. Two of these, mentioned above, were quite strikingly novel. A third grew out of the past in a more logical fashion, having to do with more general aspects of radiation—namely, the radiation of a "black body" in a condition of equilibrium,[3] whose interpretation upon a "quantum" hypothesis [4] is now a well-known but somewhat controversial matter. The earliest of the four, and perhaps the most surprising to members of the older school of physicists, was the result of the famous experiment of Michelson and Morley, in which it was found impossible to detect a relative motion

* Communicated by Prof. Arthur H. Compton, Department of Physics, University of Chicago.

[1] RÖNTGEN, *Ann. d. Phys.*, **64**, p. 1 (1895).

[2] BECQUEREL, *Compt. Rend.*, **122**, p. 420 (1896).

[3] LUMMER and PRINGSHEIM, *Verh. d. D. Phys. Ges.*, **1**, p. 23 (1899).

[4] PLANCK, *Ann. d. Phys.*, **4**, p. 553 (1901).

between the earth and the ether as small as 7.5 km. per sec.,[5] and out of which has emerged a theory of the relativity of time and space which, in the eyes of many, bids fair to absorb the whole of physical science. Suffice it here to say that in no previous period of the history of science have the results of experimentation been more replete with surprises to the investigators.

It is to the everlasting credit of Maxwell that he stood out against the rather discouraging view taken by many of the older physicists of his day.[6] To the wisdom of his enlightened attitude, as well as to the brilliance of his scientific thinking, the founding of a school of investigators whose influence is beyond calculation is largely due. Looking back, even through the scant fifty years since Maxwell's death, we readily see that the devotion of physicists of the latter half of the nineteenth century to the improvement of the accuracy of numerical measurement has led, not to the mitigated stagnation predicted, but to experimental methods which in the hands of the on-coming generation spelled the subjugation of unknown regions in the riches of nature, boundless, almost, as they seem to us now. Far from being upon the borderland of stagnation, the workers of this period were at the point of entering upon the study of one of the most important subjects of all time, the connection between electricity, matter and radiation.

Thirty-one years, since the discovery of X-rays, have now been filled largely with the work of investigating, experimentally and theoretically, these new phenomena. Many puzzling difficulties[7] with the electrodynamics of the previous century have been uncovered, and are still unsatisfactorily explained. But, on the other hand, when we reflect that only six years elapsed between the discovery of radio-activity and the advancement of an unusually satisfactory theory[8] concerning it, in the light of the previous history of science we must marvel at the rapidity of our progress and render thanks to the industry of the workers of the century preceding, who developed many of the instruments requisite for the purpose. A satisfactory interpretation of X-rays was not well defined for seventeen years after their discovery.

[5] Michelson and Morley, *Am. Jour. Sci.*, **34**, p. 333 (1887).
[6] "Maxwell's Scientific Papers," Vol. II, p. 241.
[7] A. H. Compton, *Phys. Rev.*, **21**, p. 483 (1923).
[8] Rutherford and Soddy, *Phil. Mag.*, **4**, p. 370 (1902).

Even now, over a decade later, although their association with an extremely rapid electromagnetic periodicity is beyond question, many detailed points concerning the exact nature of X-rays remain unsettled. Notwithstanding this, they have already become a powerful means for the investigation of a large variety of physical problems. Accuracy in measurement, beyond the fondest hopes of the early investigators, has been developed [9] and applied to the study of the structure of matter in a truly remarkable manner. So far, however, the surface of the possibilities has scarcely been scratched. Since the inspiration of Laue [10] and its verification by Friedrich and Knipping, in 1912, our knowledge of these phenomena has, indeed, enjoyed a marvellous progress, but it has still a much longer way to go.

In the present paper a résumé of the results of investigations upon one of the most interesting of the properties of X-rays, namely, their dispersion in material substances, will be presented. For over twenty years this minute phenomenon escaped detection. Its recent measurement and interpretation upon the basis of the theory relating matter, electricity and radiation, devised by Lorentz for optical frequencies,[11] leads to a method of *counting* the number of electrons at the various energy levels within the atoms of the elements as well as to a determination of the total numbers of extra-nuclear electrons present in their structures. It will be instructive first to review, briefly, the historical development of this work.

One of the foremost of the numerous questions which occurred to the early investigators of X-ray phenomena was with regard to the refractive indices which might be expected for different kinds of matter. Röntgen himself, in his memorable paper announcing the discovery of the new rays, described the first experiments upon this subject. Along with his observations upon their rectilinear propagation and unusual power of penetration he made studies in which he was unable to detect any refraction either in H_2O or CS_2. In the case of aluminium and hard rubber he found that, if refraction exists, the index is certainly less than 1.05. Experiments with prisms of metals heavier than aluminium were unsuccessful.

[9] See SIEGBAHN, "Spektroskopie der Röntgenstrahlen."

[10] LAUE, FRIEDRICH, and KNIPPING, *Ann. d. Phys.*, **41**, p. 971 (1913).

[11] LORENTZ, "Theory of Electrons," p. 143 (2d Ed.).

Between the years 1895 and 1912, Röntgen's results were checked by many observers, and extended to other substances. For a long time it was thought that the fact that X-rays showed practically no refraction was a good argument for an electrical "pulse" theory, based upon the assumption that no oscillators with frequencies comparable with those of X-rays exist within the molecules of the materials tried. The work of Barkla and Sadler,[12] Kaye [13] and others showed definitely, long before the advent of the crystal spectrometer, that it is incorrect to found such a theory upon this hypothesis alone. Using an absorption method for their investigations, Barkla and Sadler demonstrated the presence of distinct fluorescent X-radiations, characteristic of the elements, in the secondary rays excited by primary beams of X-rays. Kaye showed that phenomena somewhat similar to selective absorption occur when X-rays of the proper "hardness" traverse a given kind of matter.

Chapman [14] seems to have been the first experimenter to grasp the significance of these results with reference to the present problem. At least, he was the first to apply them in a search for the refraction of X-rays under more favorable conditions. The analogy with the optical case, while later shown to be not an altogether strict one, indicated that in the neighborhood of such characteristic frequencies of a substance there should be a better chance of finding phenomena of general refraction. It was also to be expected that, with frequencies sufficiently near to those which are strongly absorbed, effects similar to those of anomalous dispersion might be observed.

Accordingly a narrow beam of heterogeneous X-rays, containing the characteristic frequency of bromine, was passed through a hollow prism filled with C_2H_5Br vapor. When the record formed upon a photographic plate was compared with that of the direct beam, no evidence of refraction was found, although an index of 1.0003 could have been detected. In his experiments relative to anomalous dispersion Chapman was prepared to measure indices as small as 1.005. These were unsuccessful, also.

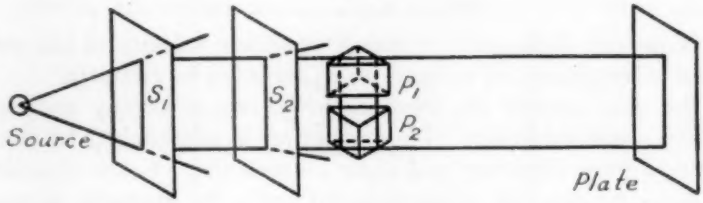
An investigation similar to Chapman's in principle was carried

[12] Barkla and Sadler, *Phil. Mag.*, **16**, p. 550 (1908).
[13] Kaye, *Proc. Camb. Phil. Soc.*, **14**, p. 236 (1907).
[14] Chapman, *Proc. Camb. Phil. Soc.*, **16**, p. 574 (1912).

out upon a prism of rhodium by Webster and Clark.[15] Monochromatic X-rays, provided by means of a crystal spectrometer and a Coolidge tube constructed with a target of rhodium, were used. From theoretical considerations the greatest refraction should occur for the γ line in the K-radiation of rhodium. Expermients were tried with the γ and β lines, the α doublet and the general radiation between the γ and β lines with no trace of refraction. An index of 1.0002 could have been detected.

Perhaps the most accurate of the experiments of this type, up to the year 1924, was one performed by Barkla.[16] Since it embodied, with improvements, all that was good in the experi-

FIG. 1.



mental procedure of his predecessors, it will be considered in some detail. Two right-angled prisms of KBr, P_1 and P_2, were arranged as shown in Fig. 1. The beam of X-rays, defined by two narrow lead slits, S_1 and S_2, separated by a distance of 50 cm., gave a line 30 mm. long and about 0.1 mm. wide upon a photographic plate, 150 cm. removed from S_2, under direct illumination. With the prisms in place the line remained straight, even after eight hours' exposure. Barkla estimates that a relative lateral displacement of 0.25 mm., corresponding to a deviation of somewhat less than 2 seconds of arc, could have been detected. Thus, for the wave-length used, 0.5 Å. U., which is very near the characteristic K-radiation of bromine, the index of refraction differs from unity by less than 5×10^{-6}.

Beginning with Chapman, the investigators in this field have been guided, largely, by Drude's [17] theory of dispersion as modified by H. A. Lorentz.[11] Lorentz's general expression follows from the superposition of our ideas concerning the atomicity

[15] WEBSTER and CLARK, *Phys. Rev.*, **8**, p. 528 (1916).
[16] BARKLA, *Phil. Mag.*, **31**, p. 257 (1916).
[17] DRUDE, "Theory of Optics," p. 382 (Mann and Millikan).

of electricity and the consequential electrical interpretation of matter upon the older maxwellian electromagnetic theory. In the region of optical frequencies it has not been feasible to make an absolute calculation of the index of refraction of a substance upon the basis of this theory of dispersion, although comparisons have been made which indicate the general correctness of the methods employed. When adapted to the case of light atoms and X-ray frequencies the development undergoes considerable simplification, and affords a direct calculation of the index of refraction which such substances should exhibit for X-rays. The required expression is obtained as follows.

The index of refraction of a substance for X-rays is defined in the usual way, namely, $\mu_r = \frac{c'}{v}$. c' represents the velocity of the X-rays in free space; v stands for their velocity in the substance whose index of refraction, μ_r, we wish to calculate.

We may assume the medium to be non-absorbing and electrically non-conducting. This condition is approached by many of the lighter elements and their compounds. Let κ represent the dielectric constant of the material and μ_p its magnetic permeability. A simple relation between μ_r, κ and μ_p is readily deduced from Maxwell's equations of the electromagnetic field, applied to the present case.[18] In general, Maxwell demonstrated that his equations signify the possibility of the production of waves of electric and magnetic force, of a wide variety of wave-lengths, which travel with velocities dependent upon the properties of the medium through which they are passing, *viz.*,

$$v = \frac{c}{\sqrt{\mu_p \kappa}},$$

where c represents the ratio between the electromagnetic and electrostatic units of current. For free space we have, by definition, $\mu_p = \kappa = 1$. Hence $c = c'$, a result which, for optical frequencies, has been verified by many careful experiments.[19] Assuming that it holds for X-rays, which is very probable indeed, although it has never been shown beyond question, it follows from our original definition of μ_r that,

$$\mu_r = \sqrt{\mu_p \kappa}.$$

[18] MAXWELL, "Electricity and Magnetism," II, p. 435 (3rd Ed.).

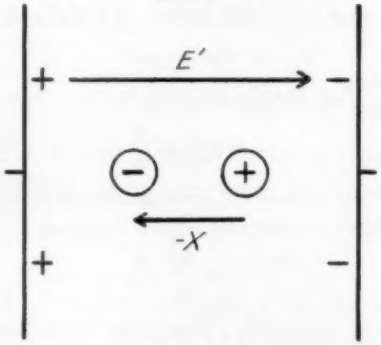
[19] ROSA and DORSEY, *Bur. of Stand. Bul. 3* (1907).

Except for ferromagnetic substances, μ_p is never greatly different from unity, even for frequencies considerably below the optical range. Since X-ray frequencies are far above these, we may adopt for our present purpose the relation,

$$\mu_r = \sqrt{\kappa}.$$

Upon the basis of the maxwellian theory this result might be expected to obtain, in many cases, for optical frequencies. Numerous observations by various experimenters have failed to give general agreement, however. Only in a limited number of special

FIG. 2.



cases is the relation found to hold. From the standpoint of present-day physics the reason for the failure lies in the fact that Maxwell did not associate the property of mass with his electric charges. When the conception of the electron, as an atomic constituent with charge e and mass m, is applied to the problem, the dielectric constant, κ, becomes a function of the frequency, ν. According to the same viewpoint, the permeability of the material is connected with the orientation of the electronic orbits within the atoms. Rapid electromagnetic oscillations should change them only very slowly, probably in much the same manner that small forces affect a gyroscope. It is reasonably certain that the above assumption, $\mu_p = 1$, is correct for all frequencies above 10^8. Hence, for X-ray frequencies, the justification is especially good.

Let us now return to the deduction of the dependence of the dielectric constant of a substance upon the frequency of the electromagnetic disturbance penetrating it, from the electron theory of matter. Consider a rectangular slab of the dielectric material between parallel plates. The application of an electric field,

$E' = 4\pi\sigma$, to the region between the plates will result in a small relative displacement, $-x$, of the balanced electrical charges which we suppose to make up the neutral atom. To the total number of these displacements in a unit volume there corresponds an electrical moment, $P = \Sigma ex$, commonly known as the "polarization," which tends to diminish the field between the plates. (Fig. 2.) The effect of this polarization throughout the volume may be referred to "fictitious" charges, P per unit area, upon the surfaces of the dielectric next the plates. For, in the case of X-rays, $P \ll \sigma$, and no correction [20] need be made for induction within the dielectric due to the displaced charges. It follows from Gauss's theorem that the field within the dielectric is given by,

$$E = 4\pi\sigma - 4\pi P .$$

But since $\sigma = \frac{\kappa E}{4\pi}$, we obtain at once,

$$\kappa = 1 + 4\pi \frac{P}{E} . \tag{1}$$

To express P in terms of measurable quantities, consider the differential equation of motion of an electron in the field, E, *viz.*:

$$m \frac{d^2x}{dt^2} + 2k \frac{dx}{dt} + q^2x = Ee \tag{2}$$

where $k \equiv$ friction constant, $q^2 \equiv$ force constant, and the other quantities are the same as before. We may suppose that $Ee = eE_0 \cos pt$. The introduction of a phase difference does not alter the essential character of the result. The solution of the equation is, then,

$$x = A \cos pt + \varepsilon^{-kt} B \cos qt . \tag{3}$$

After the oscillations have been going for some length of time, the second term may be neglected. This amounts to the assumption of a very long train of waves. We have left only the forced vibration,

$$x = A \cos pt, \text{ where } A = \frac{E_0 e}{m(q^2 - p^2)} .$$

But $p = 2\pi\nu$, and $q = 2\pi\nu_0$, in which ν_0 represents the natural frequency of oscillation of the electron. Hence,

$$x = \frac{E_0 e \cos pt}{4\pi^2 m(\nu_0^2 - \nu^2)} = \frac{Ee}{4\pi^2 m(\nu_0^2 - \nu^2)} ,$$

which gives for the electrical moment of a single elementary doublet,

[20] Richardson, "Electron Theory of Matter," p. 143.

$$ex = \frac{Ee^2}{4\pi^2 m(\nu_0^2 - \nu^2)}. \tag{4}$$

Summing this over an atom of atomic number, Z, we obtain,

$$\sum_1^Z ex = \frac{Ee^2}{4\pi^2 m} \sum_1^Z \frac{1}{\nu_s^2 - \nu^2}, \tag{5}$$

where ν_s represents the natural frequency of the s^{th} electron. If there are n atoms per unit volume of the dielectric, we find for the polarization,

$$P = n \sum_1^Z ex = \frac{nEe^2}{4\pi^2 m} \sum_1^Z \frac{1}{\nu_s^2 - \nu^2}.$$

Whence,

$$\mu_r^2 = \kappa = 1 + 4\pi \frac{P}{E} = 1 + \frac{ne^2}{\pi m} \sum_1^Z \frac{1}{\nu_s^2 - \nu^2}. \tag{6}$$

Since the summation is one of small order of magnitude, we may use the approximation,

$$\mu_r = 1 + \frac{1}{2} \frac{ne^2}{\pi m} \sum_1^Z \frac{1}{\nu_s^2 - \nu^2}. \tag{7}$$

In the case of dielectrics composed of the lighter elements, we may make a further simplifying assumption, namely, that $\nu^2 \gg \nu_s^2$. Thus we obtain, finally,

$$\mu_r = 1 - \frac{1}{2} \frac{ne^2 Z}{\pi m \nu^2}, \tag{8}$$

which represents the adaptation of Lorentz's generalized theory of dispersion to X-ray frequencies, where the frequencies are far removed from the natural frequencies of the electrons within the atoms of the substances to be considered. The result has already been checked by a number of experimenters, working along three different lines of investigation. These will be given separate consideration.

The first determinations of μ_r came as a result of deviations from Braggs' law [21] of reflection from crystalline surfaces, found by Stenström [22] during the examination of the reflection of long wave-lengths (> 2.5 Å. U.) from a crystal of sugar. Darwin [23] had predicted the probable existence of such deviations, five years

[21] W. H. and W. L. BRAGG, *Proc. Roy. Soc.*, **88**, p. 428 (1913).
[22] STENSTRÖM, Dissertation, Lund (1919).
[23] DARWIN, *Phil. Mag.*, **27**, p. 320 (1914).

previously, from theoretical considerations. In his treatment of the general problem of reflection he assumes X-ray phenomena to constitute a branch of optics, and proceeds to build up an expression for the intensity of reflection upon the basis of the electromagnetic theory. He recognizes, however, that the part played by the emission of high-speed electrons in the absorption of X-rays presents an important difficulty to his method. A second assumption, apparently necessary, is that the amplitude of a wave passing through matter diminishes exponentially with an absorption coefficient half that found for the intensity. In this connection Darwin points out that, although the absorption of an homogeneous ray is observed to be exponential, the process is probably a statistical one. In some respects, therefore, the second assumption is less satisfactory than the first. Nevertheless, his result relative to the failure of Braggs' law has now been verified. As a corollary to his theory of reflection Darwin found the relation,

$$\theta - \theta_0 = -\delta \csc\theta \sec\theta, \tag{9}$$

should hold, where θ = grazing angle of incidence, θ_0 = angle of reflection (exp'l) and $\delta = 1 - \mu_r$. He was able to calculate from this that μ_r should differ from unity by about 10^{-6}.

The corrected form of Braggs' law may be derived from purely geometrical principles if we assume that a refractive index for X-rays exists. The result is

$$n\lambda = 2D \sin\theta \left\{ 1 - \frac{\delta}{\sin^2\theta} \right\}, \tag{10}$$

in which n represents the order of the reflection, λ the wave-length, D the appropriate grating space, and the rest of the quantities are taken as before.

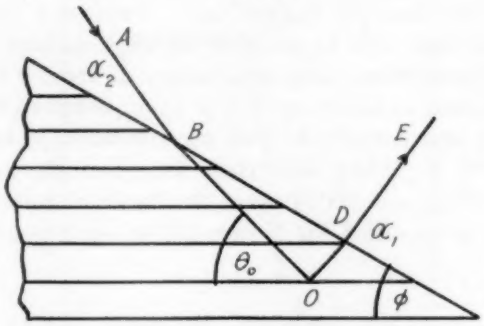
Stenström's interpretation of his observations of apparent decrements in wave-lengths determined from reflections in orders higher than the first, in this manner, has been criticized by Knipping [24] who claims that the spacial arrangement of the atoms of crystals can be adjusted to explain such differences. A more careful analysis of the situation, made by Ewald,[25] has decided most physicists against Knipping's view and for Stenström's.

[24] Knipping, *Zeits. f. Phys.*, **1**, p. 40 (1920).
[25] Ewald, *Phys. Zeit.*, **21**, p. 617 (1920).

Subsequently, Duane and Patterson,[26] and Siegbahn[27] have observed the effect, even with ordinary X-ray in the lower orders. In the latter cases, however, it was almost masked by the experimental error. Hjalmar,[28] using a photographic method, has examined with various wave-lengths the reflection from crystalline surfaces up to the tenth order. His results seem to be in fairly good agreement with the theory developed by Ewald.

A more conclusive check upon the correctness of the assumption of refraction in the explanation of these deviations from Braggs' law is due to Davis.[29] By grinding crystals so that the condition for maximum reflection is obtained within the critical

FIG. 3.



angle, which is about 15 minutes of arc for calcite, a much larger bending resulting from refraction may be obtained. The accompanying diagram (Fig. 3) is almost self-explanatory. In practice ϕ varies from 5° to 7°, being made slightly less than θ_0, the angle of reflection at the atomic planes. The grazing angle is very nearly $(\theta_0 - \phi)$, to which the bending is inversely proportional, approximately. Hence, by properly choosing ϕ, the bending may be made very large. In the beginning it is necessary to obtain a provisional value for $(1 - \mu_r) = \delta$. Usually this has been done by photographing the first and fourth orders with the unground crystal. In general, the provisional value for δ may be calculated from the expression,

[26] DUANE and PATTERSON, *Phys. Rev.*, **16**, p. 532 (1920).
[27] SIEGBAHN, *Comp. Rend.*, **174**, p. 745 (1922).
[28] HJALMAR, *Zeits. f. Phys.*, **15**, p. 63 (1923).
[29] DAVIS and TERRILL, *Proc. Nat. Acad.*, **8**, p. 357 (1922).

$$1 - \mu_r = \delta = \frac{(n \sin \theta_1 - \sin \theta_n)\,(n \sin \theta_1 + \sin \theta_n)}{2\,(n^2 - 1)} \tag{11}$$

and the data for reflection in two sufficiently different orders. The final value of δ is then secured from the equations,

$$\delta = \frac{(\sin \alpha - \sin \theta_0)\,(\sin \alpha - \sin \phi)\,(\sin \alpha + \sin \phi)}{(\sin \alpha - \sin^3 \alpha)} \tag{12}$$

for the ground crystal, where $\alpha = \frac{\alpha_1 + \alpha_2}{2}$, and

$$\sin \theta_0 = \sin \theta_1 - \frac{\delta}{\sin \theta_1} + \delta \sin \theta_1 \tag{13}$$

for the unground crystal, by a method of successive approximations. Previous observers had worked with variations of from 3 to 6 seconds of arc from the angles to be expected in the higher orders upon the basis of Braggs' law. Professor Davis and his students have been able to produce bendings as high as 218 seconds and measure them with an accuracy of from 2 to 5 seconds.

The data now available upon $\delta = 1 - \mu_r$, obtained by the application of the above methods with the condition $\nu^2 \ll \nu^2_s$, are collected in Table I. Along with them are given the corresponding theoretical values, calculated upon the basis of Lorentz's dispersion formula as modified for X-rays of the wave-lengths specified.

Table I.

Observers.	Substance.	Wave-length.	δ (obs.).	δ (calc.).
Duane and Patterson[28].....	Calcite	1.473 Å. U.	8×10^{-6}	9×10^{-6}
Duane and Patterson[28].....	Calcite	1.279 Å. U.	10×10^{-6}	7×10^{-6}
Duane and Patterson[28].....	Calcite	1.096 Å. U.	3×10^{-6}	5×10^{-6}
Davis and Terrill[29].....	Calcite	0.707 Å. U.	3×10^{-6}	1.9×10^{-6}
Hatley[30]	Calcite	0.707 Å. U.	2.03×10^{-6}	1.91×10^{-6}
Davis and Nardroff[31].....	Pyrites	0.707 Å. U.	3.35×10^{-6}	3.29×10^{-6}
Davis and Nardroff[31].....	Pyrites	0.631 Å. U.	2.82×10^{-6}	2.62×10^{-6}

The last three tests of the theory were made by Professor Davis's improved method and are consequently much more reliable. Considering the uniformity of the agreement obtained between the observed and calculated values of δ, there can be but little question about the general correctness of the interpretation advanced and its possibilities in future work. A striking confirmation of this lies in Nardroff's[32] study of iron pyrites, using

[30] Hatley, *Phys. Rev.*, **24**, p. 486 (1924).

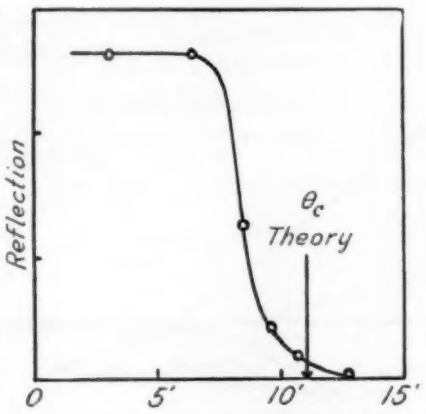
[31] Davis and Nardroff, *Proc. Nat. Acad.*, **10**, p. 60 (1920).

[32] Nardroff, *Phys. Rev.*, **24**, p. 143 (1924).

frequencies near the critical frequencies of the substance—*i.e.*, with the above condition, $\nu^2 \gg \nu^2_s$, modified to consider the effect of the K electrons in iron and sulphur. It is this aspect of the interpretation which offers the interesting possibility of *counting* the number of electrons in the K and L rings of the atoms of the elements. We shall return to Nardroff's important discovery later.

A second line of investigation which has led to a verification of the formula derived for the dispersion of X-rays, with the condition stated, is one of great simplicity and beauty, due to A. H. Compton.[33] An inspection of equation (8) shows that $\mu_r < 1$, since δ is essentially a positive quantity. Hence, it should

FIG. 4.



be possible to secure the total reflection of X-rays at sufficiently small grazing angles, *i.e.*, within a limiting angle given by the expression, $\cos \theta_c = \mu_r$. Compton calculated the value of this critical angle, θ_c, for several substances, upon the basis of the theory, and subjected the results to the test of suitably designed experiments. To show the general character of these data his curve for the reflection of a beam of monochromatic X-rays (1.279 Å. U.) from a plate of crown glass is reproduced in Fig. 4. A summary of his data for different materials, together with an observation of Davis and Terrill[29] on calcite, is given below in tabular form. Again the formula of Lorentz, in the modified form, is found to be in good agreement with experiments.

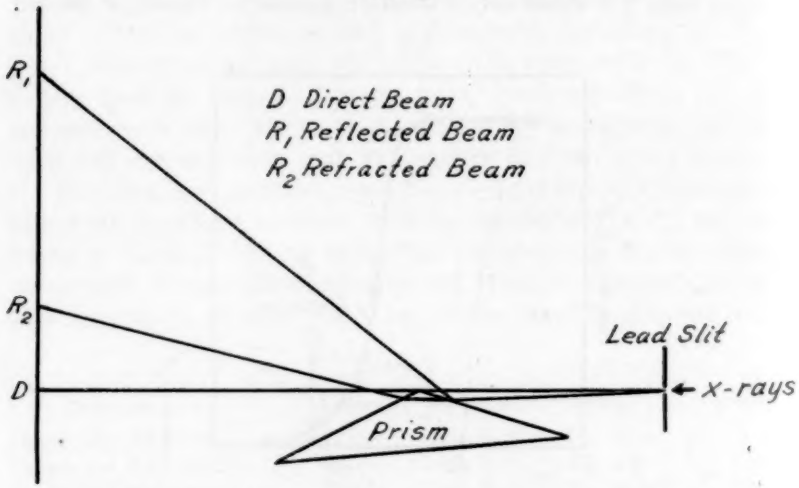
[33] A. H. COMPTON, *Phil. Mag.*, **45**, p. 1121 (1923).

Table II.

Substance.	Wave-length.	δ (obs.).	δ (calc.).
Crown glass	1.279 Å. U.	4.2×10^{-6}	5.2×10^{-6}
Crown glass	0.52 Å. U.	0.9×10^{-6}	0.7×10^{-6}
Silver	1.279 Å. U.	21.5×10^{-6}	19.8×10^{-6}
Calcite	0.707 Å. U.	1.7×10^{-6}	1.9×10^{-6}

The third test of the theory, which has been made by Larsson, Siegbahn and Waller,[34] resurrects the prism method for detecting refraction. This time it was carried through to success. Meas-

Fig. 5.



urable deviations of a narrow beam of X-rays were obtained with prisms both of amorphous and of crystalline materials. If the beam was of heterogeneous characteristic X-rays, a real spectrum was secured in which many of the lines were clearly separated. A diagram of the experimental arrangement is given in Fig. 5. The deviations measured permit of quite accurate calculations of δ, to which the theoretical results conform very well. Thus far, only the results for a glass prism of density 2.55 have been published. The writer has obtained the figures given in column five of Table III, for comparison with theory, upon the basis of an assumption made by Compton [33] regarding the composition of crown glass of about this density. It was noted that, while

[34] Larsson, Siegbahn and Waller, *Phys. Rev.*, **25**, p. 235 (1925).

for the wave-lengths 1.933, 1.750, 0.708 and 0.630 Å. U. the values found for δ (calc.) were uniformly high, those secured for 1.538 and 1.389 Å. U. were both too low. The latter determinations were considerably more accurate than the others, experimentally. Thus, the possibility of a test of the effect of the K electrons of calcium, upon the basis of these results, is suggested. We must now use a more general form of Lorentz's expression for the dispersion (*cf.* equation 7), *viz.*,

$$\delta = \frac{Ne^2}{2\pi m}\left\{\frac{n_1}{\nu^2 - \nu_1^2} + \frac{n_2}{\nu^2 - \nu_2^2} + \cdots\right\} \tag{14}$$

in which N represents the number of molecules of the substance per unit volume, n_1, n_2, . . . the number of electrons per molecule with natural frequencies ν_1, ν_2, . . . , and the other symbols are to be taken as before.

TABLE III.

Observers.	Substance.	Wave-length.	δ (obs.).	δ (calc.).
Larsson, Siegbahn and Waller[35]	Glass	1.933 Å. U.	12.38×10^{-6}	12.79×10^{-6}
" " "	Glass	1.750	10.00×10^{-6}	10.49×10^{-6}
" " "	Glass	1.538	8.12×10^{-6}	8.10×10^{-6}
" " "	Glass	1.389	6.64×10^{-6}	6.60×10^{-6}
" " "	Glass	0.708	1.64×10^{-6}	1.71×10^{-6}
" " "	Glass	0.630	1.22×10^{-6}	1.35×10^{-6}
Davis and Slack[36]	Aluminium	1.537	8.40×10^{-6}	8.36×10^{-6}
" "	Aluminium	0.708	1.68×10^{-6}	1.77×10^{-6}

Calcium shows critical absorption at 3.063 Å. U., according to Fricke.[37] For the other elements appearing in the composition of glass the absorption bands are relatively much higher and may be neglected for the present. Hence for the purpose of our calculations, we obtain,

$$\delta = \frac{Ne^2}{2\pi mc'^2}\left\{n_1\lambda^2 + \frac{n_2\lambda^2\lambda_c^2}{\lambda_c^2 - \lambda^2}\right\} \tag{15}$$

In the denominator of the constant multiplier, c' represents the velocity of light, with which, in free space, the velocity of X-rays is supposed to be in agreement. Applying equation (15)

[35] LARSSON, SIEGBAHN and WALLER, *Naturwis.*, **12**, p. 1212 (1924).
[36] DAVIS and SLACK, *Phys. Rev.*, **27**, p. 18 (1926).
[37] FRICKE, *Phys. Rev.*, **16**, p. 202 (1920).

as outlined above, we find values for δ, in the cases pointed out, as follows:

Wave-length.	δ (calc.).
1.538 Å. U.	8.14×10^{-6}
1.389 Å. U.	6.63×10^{-6}

The corrections are, therefore, not only in the right direction but of about the required magnitude.

Included in Table III are two observations made with prisms of aluminium by Davis and Slack,[36] who have introduced the use of a double X-ray spectrometer to improve the accuracy obtainable in this type of investigation. Since critical absorption in aluminium comes at 7.947 Å. U., the simpler expression (8) may be used for comparison with the theory, in the case of the wave-lengths used. The calculated values for δ, which the authors give, are in accord with their experimental results.

The effect of the natural frequencies of the K electrons of iron and sulphur has been carefully investigated by Nardroff [32] in an examination of a crystal of iron pyrites, ground according to the suggestion of Davis,[29] previously cited. The accuracy of his work is surprising, and gives great promise that an extension of the method to the study of other elements will, in effect, give an actual count of the number of K and L electrons which they are commonly supposed to contain. In order to apply the formula of Lorentz to the case of iron pyrites, Nardroff has rewritten equation (14) in the following form:

$$\delta = \frac{Ne^2}{2\pi m}\left\{\frac{K_{Fe}}{\nu^2 - \nu^2_{Fe}} + \frac{K_S}{\nu^2 - \nu^2_S} + \frac{(Z_{Fe} - K_{Fe}) + 2(Z_S - K_S)}{\nu^2}\right\} \qquad (16)$$

Here K_{Fe} and K_S refer to the number of electrons in the K rings of the iron and sulphur atoms, respectively, Z_{Fe} and Z_S to their respective atomic numbers, and ν_{Fe} and ν_S to their critical absorption frequencies, which have been taken to be 1.740 and 5.023 Å. U. The copper K-rays are sufficiently close to these to give a marked dispersive effect, and, consequently, were chosen for the investigation. Nardroff's results are tabulated below:

		δ (calc.).			
Wave-length.	δ (obs.).	$K = 0$.	$K = 1$.	$K = 2$.	$K = 3$.
1.537 Å. U.	17.6×10^{-6}	15.58	16.58	17.60	18.61×10^{-6}
1.389 Å. U.	13.2×10^{-6}	12.69	13.12	13.53	13.95×10^{-6}

In the case of the copper K_{α_1} line (1.537 Å. U.) the *count* for the number of K electrons in iron and sulphur is definitely two. For the copper K_{β_1} line (1.389 Å. U.) it is not so convincing, although about right. It is to be remembered, however, that in the latter case the frequency used is farther removed from the critical absorption frequencies and that the differences between the calculated results are correspondingly less marked. This distinction is especially important with respect to the critical wave-length of iron (1.740 Å. U.).

Perhaps the most striking resemblance which the results of investigations of this kind bear to the phenomena of optics lies in the recent discovery by Larsson, Siegbahn and Waller [38] of the anomalous dispersion of X-rays in calcite and gypsum. Definite discontinuities were found, both at the calcium (3.063 Å. U.) and at the sulphur (5.023 Å. U.) critical absorption frequencies. In these data, also, the optimistic investigator can almost see the beginnings of an experimental distinction between the classical cases of "friction" and "non-friction" with respect to the response of the electronic vibrators under the influence of the primary rays. The indications are that the branches of the dispersion curves are rounded off and do not approach infinity near the absorption bands. Davis and Slack,[39] in a study of the refraction of the copper K lines by a prism of copper, arrived at a similar conclusion. In the case of X-rays, therefore, the behavior is quite like that of ordinary light near the critical resonance frequencies of a substance. Graphically, this is represented in Fig. 6. But it is too soon, perhaps, to advance any very serious views upon the question.

From the standpoint of the special theory of relativity the result, $\frac{c'}{v} = \mu_r < 1$, is a bit puzzling. To the casual observer it appears contrary to the second postulate, from which we infer that v can never be greater than c'. Harmony is restored when we reflect that an individual wave may travel with a velocity above that of the train of waves of which it is a part. In the theory of relativity it is the velocity of the train of waves with which we are concerned, *e.g.*, in the process of signalling from one system

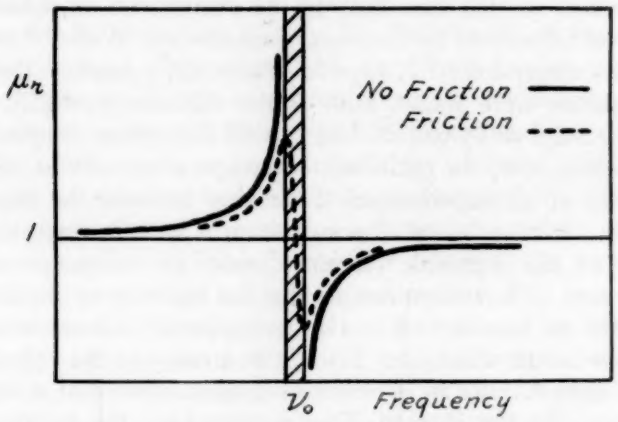
[38] LARSSON, SIEGBAHN, and WALLER, *Jour. Phys. et Rad.*, (6)7, p. 228 (1925).

[39] DAVIS and SLACK, *Phys. Rev.*, **25**, p. 881 (1925).

of reference to another. The front of the wave-train may be vanishing and the rear building up at the same rate, less than c', and yet each individual wave in between may be travelling so that its velocity, v, is greater than c'.

This sort of a reconciliation of the result, $\mu_r<1$, with the postulate of the special relativity, involves a difficulty with the "pulse" theory of X-rays as developed by J. J. Thomson.[40] For, if X-rays consist of single pulses of electromagnetic force, their index of refraction would necessarily be greater than unity.

Fig. 6.



Thomson evades the trouble by a theoretical demonstration that, on passing through even a very small quantity of matter, a pulse is transformed into a series of waves.

In conclusion, laying aside all of the more recent attempts at an application of the success of Lorentz's dispersion formula in the realm of X-ray frequencies to the problems of the structure of matter, one should note particularly the striking agreement of the theory with experimental results in the simplest cases, where the natural frequencies of the electrons within the atoms can be neglected. The origin of the equation corresponding, (8), is similar to the well-known derivation of the expression for the dispersion of light in metals, where it is supposed that the electrons may be considered to be very loosely bound. The good agreement secured in three different lines of experimental investi-

[40] Thomson, *Phil. Mag.*, **45**, p. 172 (1898).

gation constitutes a new and more direct test of the optical theory of dispersion than has heretofore been possible. Granting the correctness of the theory, we now have an accurate and an independent method for investigating the total numbers of the electronic vibrators in the atoms of the elements.

It should be pointed out, also, that any quantum theory of dispersion must take account of the fact that, near the critical absorption frequencies, the reactions of the electrons within the atom seem similar to those of any other electromechanical system. The theory of Lorentz is based upon a resonance principle. Its recent successes in explaining phenomena observed in the region of X-ray frequencies are matters of great importance to quantum theories. This, however, is by no means to be interpreted as a tendency to return to the viewpoint of the past century. The electrodynamics of that day has found its extension in the general theory of relativity, whose influence upon problems of the nature of those mentioned in the opening paragraph of this discourse is now beginning to be felt.[41]

My best thanks are due Prof. Arthur H. Compton, whose discussions and generous suggestions have led to the preparation of this paper.

Dust Explosion Expert Talks to Fire Fighters.—The danger to life and property from dust explosions in industrial plants and the precautions to be taken in fighting resulting fires were outlined in an address before the Convention of the International Association of Fire Fighters, at Philadelphia, October 6th, by David J. Price, of the United States Department of Agriculture, in charge of dust explosion investigations. Dust explosions in industrial plants occur in various ways, most of them taking place during normal operation of the machinery creating the dust. In some instances, however, explosions have taken place during the fighting of fires, endangering the lives of the firemen.

From the experience that some fire departments have had in fighting fires in industrial establishments where explosive dusts are produced, it is quite evident that firemen should become acquainted with the work that has been done on this subject and understand fully the danger involved in fighting such fires.

In connection with the work that has been done on dust explosion prevention by the Department of Agriculture, it has been found that approximately 28,000 industrial plants in the United States alone are subject to the dust explosion hazard and, therefore, should

[41] LUNN, *Phys. Rev.*, 21, p. 711 (1923).

adopt precautionary measures. These plants employ approximately 1,324,422 persons and manufacture products of an annual value in excess of $10,000,000,000.

Two hundred and eighty explosions of this character have been recorded. In seventy of these cases 459 persons were killed and in ninety-two explosions 760 were injured. The property loss amounted to an average of $240,000 for each explosion.

It is common knowledge, according to Mr. Price, that dynamite or gasoline or a process in which inflammable oils are used constitutes a serious danger to firemen. Firemen must understand, he said, that other substances, such as dusts or chemicals, are just as dangerous and proper precautions should be adopted.

Two recent explosions, he said, brought attention to the need of training firemen or instructing them in the proper way of fighting fires where a dust explosion hazard exists. While fighting a fire in a wood dust storage tank following an explosion in a wood-working plant, two firemen were burned when they opened a tank to allow the dust to flow out. The suspended dust exploded when it was ignited by a flame in the tank and the flash enveloped the firemen. Four days later six firemen lost their lives and six others were severely burned while fighting a fire in another wood-working plant. When the fire in the dust bin apparently had been extinguished, the firemen opened the bottom of the bin and allowed the dust to run out on the floor approximately 15 feet below. As it fell to the floor a dust cloud was formed. When it was ignited by fire which apparently had been smouldering in the bin, or by the fire from a nearby furnace, a terrific explosion occurred, costing the lives of six firemen.

Precautionary measures were suggested by Mr. Price for the guidance of firemen in such cases. Instead of immediately removing the contents of bins, in which a fire has occurred and is apparently extinguished, it would be better practice, he said, to flood the bin and thoroughly wet down material before undertaking to remove the contents. Also it would be preferable, he said, to use a spray nozzle for this purpose instead of the heavy stream from the hose and thus avoid stirring up a dust cloud when wetting down dusts stored in piles.

He further urged the systematic inspection of plants to acquaint the firemen with any dust explosion hazards. Such advance information on a particular plant would be valuable to them if they were called on to fight a fire.

NOTES FROM THE NELA RESEARCH LABORATORY.*

ON THE ANODE GLOW IN NEON.

By Richard Rudy.

If the anode of a discharge tube is moved toward the cathode, at a certain distance the anode glow disappears and the potential difference decreases by an amount equal to the ionization potential of the gas (anode fall of potential). Two explanations have been proposed. It may be assumed that for short distances the primary electrons have enough energy left to produce ionization near the anode and reduce the negative space charge. Thus, in argon at 10 mm. pressure, 200-volt electrons would still have energy above 15.4 volts after having travelled 45 mm., *i.e.*, after about 3000 collisions. From the probability of ionization, however, it may be concluded that 200-volt electrons lose their power to ionize argon after about thirty collisions and 100-volt electrons after about fifteen collisions. At 1 cm. pressure this gives a range, if this term may be used, of 1.5 mm. for 200-volt electrons and .7 mm. for 100-volt electrons. Actually, when the break in the collector characteristic was considered, these distances were slightly too long, on account of the loss due to radiation, deflection, and recombination. It seems more probable that for short distances the positive ions produced near the cathode diffuse towards the anode in sufficient number to destroy the negative space charge.

With an electrode of suitable size and with currents of the order of a fraction of a milliampere, the space charge is not strong enough to cause an anode fall. It was found that in neon the distance at which the anode glow disappears was (between disc electrodes of 1-inch diameter), *e.g.*:

At 9.7 mm. Hg, 5 cm. for a current of .1 milliampere;
4 cm. for 1 milliampere; 5.7 cm. for 2 milliamperes.
At 6.7 mm. Hg, > 6 cm. for a current of .1 milliampere;
5 cm. for 1 milliampere; 4.7 cm. for 2 milliamperes.

At very small current intensities the discharge current had many features in common with the thermionic discharge below the

* Communicated by the Director.

saturation current. Thus, at 9.7 mm. Hg, the only glow visible for 2 microamperes was near the anode, the electrons accumulating energy for this glow all the way between the electrodes. The glow reached the cathode as the current was increased and a cathode fall was built up (10 microamperes). At lower pressures, a small red cloud of light could be seen to travel from the anode to the other electrode each time the current was established. With alternating or intermittent current this displacement must produce moving striations across the tube in very pure gas. A first transient flash of light was almost always observed near the (carbon) cathode.

ON THE STRUCTURE OF THE SPECTRUM OF NITROGEN N II AND THE PRODUCTION OF THE ARC SPECTRUM N I.

By Richard Rudy.

A. FOWLER and F. Croze have determined the important levels in the ionized nitrogen atom N^+. In this note a new ^3P term is established which shows the structure of the ionized nitrogen atom levels to be entirely according to the theoretical prediction for an element of the fourth column. The fundamental level of N^{++} being ^2P, the fourth electron may be added in one more 2_2 orbit to form N^+, with 2^3P, $2'D$, $2'S$, as the lowest levels. Or this electron may be brought upon a 3_1 level, which gives 3^3P and $3'P$ term, the lowest levels from which spectral lines are actually known. Among these spectral lines the ^3PP group near 4631, 4447 and 3996 has been observed as absorption lines in stellar spectra. The next possible case is to add the valence electron in a 3_2 level; under the influence of the core and the other L electrons the 3^3D, 3^3S, $3^3P'$, $3'D$, $3'P'$, $3'S$ levels are then formed. 4447 being the $'D_2{}'P$ transition, line 4425.9 may be written as $^3P'D$, 3996 as $'PP'$. Adding the electron in a 3_3 level produces the 3^3F, $3^3D'$, 3^3P, $3'F$, $3'D$ and $3'P''$ levels. The term value for a 3_3 orbit in the field of a point charge 2 is equal to 48772; if in N^+ the 3_3 orbit lies entirely outside the core, the terms due to addition of it to the core would be expected to have this value and the assumed term values would have to be increased by nearly 20,000. There is one more level known, 4^3P due to a 4_1 electron which furnishes similar terms as a 3_1 electron. The new 3^3P terms are 30132, 30160, 30202; they are in reverse order, the largest term being P_2. The lines 4478, 4460, 4465,

4507 (?) belong to a $^3D^3P$ group, 5452, 5454, 5463, 5478, 5480 to a $^3PP''$ group; 5007, 4994, 4987 as shown by the Zeeman effect, are the $^3P^3S$ group.

On adding one more electron to N^+ in a 2_2 orbit, neutral N is obtained with 2^4S, 2^2D, and 2^2P as fundamental orbits, giving rise to the nitrogen resonance lines. The development of the next higher terms 3^4P, ^2P, ^4D, $^4P'$, ^4S, ^2D, $^2P'$, ^2S, agrees also with the recent theory, but some of the terms due to the 3_3 orbit ^4F, $^4D'$, $^4P''$, ^2F, ^2D, $^2P''$ seem again to be less well known owing to the incomplete data for infra-red lines.

The assertion has repeatedly been made, of late, that in order to isolate the arc spectrum of nitrogen from the spark spectrum, the presence of helium in the discharge tube is necessary. If, however, the self-induction in a spark circuit is increased, the air lines disappear, as is known, and the ultimate rays of the electrode material become prominent. When working with Ag or W electrodes, it was found that as the self-induction was increased a new line spectrum appeared. These lines were measured, and it was found that they belong to the arc spectrum of neutral nitrogen which is thus completely separated from the spark spectrum. Almost all the wave-lengths agree with those given by Hemsalech and Merton and Pilley. The production of the arc spectrum of nitrogen seems, therefore, not essentially different from the excitation of the arc spectrum of other gases, *e.g.*, oxygen.

REGULARITIES IN THE ARC SPECTRUM OF CARBON (C I) AND K+.

By Richard Rudy.

THE lines 1658.18, 1657.96, 1657.42, 1657.04 and 1656.33 (Kayser) may be written as the $2^3P3^3P'$ group:

2^3P_2		2^3P_1		2^3P_0	
		60315			$3^3P_0'$
		15			
60307	30	60334.7	15	60349	$3^3P_1'$
41		41			
60348	26	60374			$3^3P_2'$

Lines 1561.97, 1560.76 and 1560.34 as the $2^3P3^1P'$ group
64042.8 (28) 64071.3 (17) 64088.8.

Line 2478.6 is due to the $2'S3'P$ transition. The ^3P separation is found once more in the possible PP lines 1329.60 and 1329.07;

a 3^3S term is indicated by lines 5554.7 (to $3^3P'$) and 1277.32 (to 2^3P).

The atomic number of A being 18 and that for K 19, it is to be expected that the spectrum of K^+ will be similar to that of A. The lines of K^+, however, will be of higher frequency than corresponding lines of A in consequence of the greater charge of the core with respect to the emitting electron. The following list has been prepared to show how close the resemblance is; the ratio of the wave-numbers is about 1.95 almost throughout the whole table. The comparison may be extended to higher levels.

		S_2 or $^1P_1$	S_3 $^3P_0$	S_4 $^3P_1$	S_5 $^3P_2$
$^1S_0$	p_1	13,323 28,314.6		14,972 31,539.8	
$^3P_1$	p_2	12,097 23,673.3	12,943 24,985.2	13,746 26,898.7	14,353 27,627.8
$^3P_0$	p_3	11,890 23,310.5		13,539 26,536.2	14,146
$^3P_2$	p_4	11,732 23,200.2		13,381 26,425.2	13,988 27,154.6
$^1P_1$	p_5	11,654 21,693.2	24,094.3	13,303 26,007.0	
$^3D_2$	p_6	10,837 21,693.2		12,487 24,917.6	13,094 25,647.4
$^3D_1$	p_7	10,687 21,069.2	11,533 22,381.8	12,336 24,294.6	12,943 25,023.6
$^1D_2$	p_8	10,217 20,224.0		11,867 23,448.8	12,474 24,178.6
$^3D_3$	p_9	19,925.5		23,153.2	12,319 23,881.1
$^3S_1$	p_{10}	16,746.8	18,085.5	10,352 19,972.0	10,958 20,701.4

NOTES FROM THE RESEARCH LABORATORY, EASTMAN KODAK COMPANY.*

DISPLAY ENLARGEMENTS FROM SINGLE FRAME MOTION PICTURES.[1]

By K. C. D. Hickman.

THE highest quality enlargement obtainable from a single motion picture frame cannot be secured unless the following precautions in descending order of importance are taken: (1) The light source must be highly diffused. (2) The last diffusion screen must be as near as possible to the negative. (3) The negative must be placed between glasses quite free from defects and dust. (4) The negative may be embedded in a liquid of the same mean refractive index.

The paper describes methods of sandwiching the film with glycerin or xylol between glasses before placing in the projector.

THE EFFECT OF PROJECTION LENS FLARE UPON THE CONTRAST OF A MOTION PICTURE IMAGE.[2]

By L. A. Jones and C. Tuttle.

A STUDY is made of the relative characteristics of a motion picture positive and its screen image. It is concluded that: (1) The veiling brightness due to flare is directly proportional to the average transmission of the projected positive. (2) The flare-forming characteristic of a lens may be expressed as the ratio of the flare brightness to the average brightness of the picture. (3) The effect of flare upon the contrast characteristics of the picture can be computed from a knowledge of certain characteristics of the positive. (4) The effect of lens flare on quality of tone reproduction is to warp the shape of the reproduction curve and depress the contrast.

* Communicated by the Director.

[1] Communication No. 275 from the Research Laboratories of the Eastman Kodak Company and published in *Trans. Soc. Mot. Pict. Eng.*, No. 25, 1926, p. 49.

[2] Communication No. 277 from the Research Laboratories of the Eastman Kodak Company and published in *Trans. Soc. Mot. Pict. Eng.*, No. 25, 1926, p. 153.

NOTE ON THE STRENGTH OF SPLICES.[3]

By S. E. Sheppard and S. S. Sweet.

PROPER film splicing should be done automatically. It was found that there is no difference in strength between the 0.156-inch and the 0.078-inch splice. The use of a proper scraper with a square edge is recommended.

Time increases the strength of splices, but this effect may be replaced largely by heat. Excess use of cement should be avoided because it causes buckling and warping.

A "BUBBLER" LABORATORY FRACTIONATING COLUMN.[4]

By H. T. Clarke and E. J. Rahr.

A NEW type of laboratory distillation column in which the ascending vapor is washed by the reflux liquid in bubbling traps on the counter-current principle.

This column, which is constructed entirely of glass and contains no movable parts, may readily be made by an amateur glass-blower.

Liquids can be separated more rapidly with this apparatus than with the usual forms of laboratory column. Thus on distilling a mixture of two litres each of commercial benzene and toluene through a still head containing eight bubbling traps, 1480 c.c. of benzene boiling at 79–82° was obtained in seven and a half hours, while on continuing the distillation the residue boiling above 109° amounted to 1455 c.c.

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[3] Communication No. 276 from the Research Laboratories of the Eastman Kodak Company and published in *Trans. Soc. Mot. Pict. Eng.*, No. 25, 1926, p. 142.

[4] Communication No. 278 from the Research Laboratories of the Eastman Kodak Company and published in *Ind. Eng. Chem.*, **18**, 1092, 1926.

NOTES FROM THE U. S. BUREAU OF CHEMISTRY.*

THE pH WITH QUINHYDRONE ELECTRODE.[1]

By Louis E. Dawson.

[ABSTRACT.]

THE elements of the quinhydrone electrode and the use of this electrode for the determination of the pH of solutions are considered. The new electrode apparatus described is especially well suited for use in measuring the pH of solutions which contain suspended matter, such as soil suspensions and raw or limed cane juice and with quinhydrone which settles out on standing. The apparatus is also for use in measuring the pH of solutions (such as some sugar solutions) heavier than the saturated potassium chloride used as a bridge solution. Data on the effect of dilution upon the pH of sugar solutions indicate that measurement of pH at two concentrations and extrapolating to a higher concentration will not always give the correct pH value. Sometimes, according to the nature of the solution, the percentage by weight of solids in the solution affects the pH in a logarithmic manner and at other times the pH is a straight line function of the percentage of solids.

DISTRIBUTION OF VOLATILE FLAVOR IN GRAPES AND GRAPE JUICES.[2]

By J. W. Sale and J. B. Wilson.

[ABSTRACT.]

ANTHRANILIC acid ester in grapes, grape products, and imitation grape preparations can be determined quickly and accurately by a new method developed in the Bureau of Chemistry of the United States Department of Agriculture.

The content of anthranilic acid ester and of total volatile esters is a true measure of the intensity of aroma in grapes and grape juices.

The anthranilic acid ester in eighty-four samples of whole grapes, representing about fifty-five varieties, varied from 0.00

* Communicated by the Chief of the Bureau.

[1] Published in *Sugar*, **28**, 211–214, 262–264; 310–312; 369–370 (1926).

[2] Published in *J. Agr. Research*, **33** (August 15, 1926): 301–310.

to 3.80 mgm. per kilogram. The volatile esters and volatile acids in fifty samples, representing about thirty-four varieties, varied from 6 to 366 and from 3 to 121 mgm. per kilogram, respectively.

Anthranilic acid ester has not been found in the fruit of *Vitis vinifera*. The determination of this ester, therefore, appears to be of value in identifying species.

Contrary to general opinion, the volatile flavor of grapes is not contained almost wholly in the skins. Substantial proportions are found in the pulp. Nearly as much volatile flavor remains in the pomace as is contained in the expressed juices.

Anthranilic acid ester tends to disappear from grape juice which is stored. This fact may explain the deterioration in flavor of certain commercial bottled grape juices.

The anthranilic acid ester in fourteen samples of commercial bottled grape juices of unknown origin varied from 0.00 to 1.35 mgm. per litre. The volatile esters in eight of these samples varied from 5 to 29 mgm. per litre.

A FIELD METHOD FOR DETERMINING THE OIL STRENGTH OF SPRAYS.[3]

By E. L. Griffin (Bureau of Chemistry) and C. H. Richardson (Bureau of Entomology).

[ABSTRACT.]

THE Babcock method for the determination of butter-fat in milk and cream is modified to give the per cent. by volume of oil in concentrated and spray-strength petroleum oil emulsions. The modified method is adaptable to emulsions containing soap, cresol, glue and probably other organic emulsifying agents, and can be used during spraying operations in the field. It is simple and can be used by non-technical men.

MODIFICATIONS OF METHODS FOR MAKING COLD-MIXED OIL EMULSIONS.[4]

By C. H. Richardson (Bureau of Entomology) and E. L. Griffin (Bureau of Chemistry).

[ABSTRACT.]

A COLD-MIXED lubricating oil emulsion can be made by the addition of 8 liquid ounces of crude cresylic acid, cresol U.S.P.,

[3] Published in *J. Econ. Entomology*, 19 (June, 1926): 522–525.

[4] Published in *J. Econ. Entomology*, 19 (June, 1926): 525–529.

or cyclohexanol to the usual proportions of potassium fish oil soap and oil called for in the boiled emulsion formula, adjusting the water content to give about 68 per cent. oil by volume. The paste of oil, soap, and cresylic acid first obtained may be diluted at once with water to form a stock emulsion, or stored for future use. It will keep indefinitely if evaporation is prevented, but should be mixed with a little water before being poured into the spray tank. When diluted to spray strength, this emulsion has the stability and small droplet size characteristic of diluted miscible oils. Any petroleum oil from kerosene to lubricating oil of high viscosity can be used to prepare this emulsion. A good cold-mixed emulsion can also be made with two gallons of oil and one quart of potassium fish oil soap. The soap-oil paste may be stirred at once into 3 quarts of water to make a stock emulsion or held for future use. Such emulsions appear to be as stable as those prepared according to the usual boiled emulsion formula.

SO-CALLED HABITUATION TO "ARSENIC."[5]

By Erich W. Schwartze and James C. Munch.

[ABSTRACT.]

THE Bureau of Chemistry undertook a series of experiments to find an answer to the question, Can habituation of man or the higher animals to arsenious oxide be obtained?

No certain habituation of cats to "arsenic" fed in increasing doses at suitable intervals could be shown. The loss of appetite and slowness of eating which developed, or which cats voluntarily induced, complicates an analysis of the data. This enables the cats to retain more food than they would had the meal been eaten at once and a portion subsequently vomited. This "pseudo" tolerance is not regarded by the investigators in any sense as a real tolerance.

Cats fed daily doses of dissolved arsenious oxide ("arsenic") in sub-emetic concentration developed no habituation; on the contrary, they showed a decline in appetite. They vomited once or twice early in the experiments, obviously from the cumulative superimposition of the effects of the sub-emetic doses, and thereafter regulated the food intake, apparently to avoid the emesis.

The criterion of habituation has been the threshold emetic dose, which is much lower than the concentration necessary to

[5] Published in *J. Pharma. and Exp. Therapeutics*, **28** (Sept., 1926): 351–360.

produce immediate and complete emesis. The failure of cats to withstand such doses successfully is a fair criterion of the improbability of developing any noteworthy systemic or gastro-intestinal habituation to "arsenic" by feeding—the only manner in which habituation to "arsenic" has been claimed to have been produced in man or laboratory mammal.

PECTIC ACIDS.[6]

By E. K. Nelson.

[ABSTRACT.]

EXPERIMENTS recently concluded in the Bureau of Chemistry show that the pectic acid obtained by the method of Wichmann and Chernoff (*J. Assoc. Official Agr. Chem.*, **8**, 129 (1924)) is identical with the digalacturonic acid (A) of Ehrlich and Sommerfeld (*Biochem. Z.*, **168**, 263–323 (1926)).

CHEMICAL COMPOSITION OF RICE OIL.[7]

By George S. Jamieson.

[ABSTRACT.]

THE oil extracted from rice bran by ethyl ether was analyzed in the Oil, Fat and Wax Laboratory of the Bureau of Chemistry.

A sample of the extracted rice oil with an acid value of 73.7 contained 14.7 per cent. of saturated and 74.3 per cent. of unsaturated acids. The oil had an iodine number of 99.9 and a saponification value of 185.3. The composition of the oil was as follows:

	Acid.	Per cent.
Glycerides of.....	Oleic	41.0
	Linolic	36.7
	Myristic	0.3
	Palmitic	12.3
	Stearic	1.8
	Arachidic	0.5
	Lignoceric	0.4
	Unsaponifiable matter	4.6

Sterols, which amounted to about 25 per cent. of the unsaponifiable matter, were isolated. The several fractions of sterols ranged in their melting-points from 137° to 143° C. Also a small quantity of what appears to be melissyl alcohol was obtained from the unsaponifiable matter.

[6] Published in *J. Am. Chem. Soc.*, **48** (Sept., 1926): 2412–2414.

[7] Published in *J. Oil and Fat Industries*, **3** (Sept., 1926): 256–261.

NOTES FROM THE U. S. BUREAU OF MINES, DEPARTMENT OF COMMERCE.*

HYDROGEN SULPHIDE POISONING IN THE TEXAS PANHANDLE, BIG LAKE, TEXAS, AND McCAMEY, TEXAS, OIL FIELDS.

By W. P. Yant and H. C. Fowler.

HYDROGEN SULPHIDE is probably the most toxic gas associated with crude oil. Hydrocarbon (petroleum) vapors themselves are harmful to the human system, but hydrogen sulphide, when present, is usually more important from the standpoint of health and safety. These conclusions were reached in an investigation of the toxic gases encountered in the transportation and refining of high-sulphur petroleum. The results of that investigation are presented in Bureau of Mines Bulletin 231. Although the writers of Bulletin 231 paid no direct attention to the production of oil in the field, they attributed to hydrogen sulphide reports of accidents caused by gas in the oil fields of Mexico. During the development of oil fields in Texas, a "poison gas" was encountered that constituted a decided health and safety hazard. An investigation of this gas was conducted by the Bureau of Mines in the Panhandle, the Big Lake, and the McCamey fields, Texas.

The work undertaken in each field included: (1) Examination of the gas coming from representative wells, also analyses of the gas-air mixtures to which the workmen were or might be exposed; (2) observation of symptoms of poisoning and severity of these symptoms; (3) observation of the conditions of exposure that produced the symptoms; and (4) study of ways and means of protection and prevention.

The whole survey was made in order to determine general conditions relative to the hydrogen sulphide hazard in the three fields rather than a detailed study of individual properties. However, representative data were gathered, and, from these findings, recommendations have been made that should help reduce the hazard in these and similar fields.

* Communicated by the Director, Bureau of Mines.

The prevailing conditions in the Panhandle, Big Lake, and McCamey fields were similar to those reported in Bulletin 231. The characteristic odor of hydrogen sulphide could be detected almost anywhere in the field; also there was a pronounced darkening of white lead paint on houses, of brass valves and fittings, and of silver money. The symptoms caused by this gas—both acute (as unconsciousness) and subacute (as eye and respiratory tract irritation)—were identical with those produced by hydrogen sulphide. With the exception of slight gasoline-vapor intoxication and the possible existence of gas-air atmospheres containing an insufficient amount of oxygen to support life, no indications of other toxic gases were noted. The examination of the gases and gas-air mixtures were therefore confined to analyses for hydrogen sulphide content. Further details are given in Serial 2776, recently issued by the Bureau of Mines.

RECENT PROGRESS IN SLATE TECHNOLOGY.

By Oliver Bowles.

SINCE 1922, when the Bureau of Mines issued a report covering the slate industry in detail, changes in technology have taken place which have an important bearing on the industry. A study of these changes and their effects on the industry has just been completed by the writer. Though the value of slate for roofing, structural, blackboard, sanitary, and electrical uses is generally recognized, it has many competitors. To meet this constantly increasing competition producers are promoting economies in manufacture and improving processes, thereby lessening costs of production, and are placing on the market products of the highest possible quality, thus creating satisfaction and confidence on the part of the user. This endeavor to place the industry on a better basis, both as regards processes and products, is shown in the recent developments in technology.

Among these developments are more efficient mills for manufacture of roofing slates, utilizing specially designed saws in cutting slates which largely replace hand methods of splitting and trimming, use of power-driven machinery in handling blocks, finished slates, and waste, thereby increasing the output and saving a considerable percentage of slate wasted under old hand

methods. Besides the circular saw, a modified type of gang saw has been developed, and is in successful use in several slate mills. Other labor-saving devices include an air-driven slate splitter, power-driven punching machines, and trimming machines for heavy slates. Various new uses are being developed. A new slate product, struco, consists of slabs lacquered in various colors, which overcomes the objection of sombre color, where natural slate color is not suitable to the architectural pattern. Natural variegated slates of irregular shapes produce attractive rustic effects and are coming into insistent demand. Irregular fragments usually discarded are now finding pleasing application in walks, floors, and pavements. Floor tile and sawn shingles are being manufactured, and slate veneered shingles with a composition backing are being tested. Further details are given in Serial 2766 of the Bureau of Mines, recently published.

COMPOSITION OF THE LIGHT OILS FROM LOW-TEMPERATURE CARBONIZATION OF UTAH COALS.

By R. L. Brown and R. B. Cooper.

In an investigation of the distillation products from low-temperature carbonization of Utah (Mesa Verde bed) coal, the composition of the light oils that remain in the gas distilled from the coal under definitely known conditions was determined. The coal was heated at a maximum temperature of about 725° by means of superheated steam. Analysis of the coal (as received) showed 3.4 per cent. moisture, 42.9 per cent. volatile matter, 46.2 per cent. fixed carbon, and 7.5 per cent. ash. The oil recovered amounted to 7 c.c. per kilogram or 1.7 gallons per ton of coal. It consisted of 8 per cent. isopentane, 2 per cent. n. pentane, 30 per cent. amylenes, 8 per cent. hexanes, 19 per cent. hexene, 7 per cent. heptane, 6 per cent. heptene, 4 per cent. olefins, 8.5 per cent. octenes, 7.5 octanes and above. The amount of acids and bases was very slight, a little pyridine was found. Further details will be found in a paper presented before the American Chemical Society meeting in Philadelphia, to be published in a forthcoming issue of *Industrial and Engineering Chemistry*. The work was conducted in coöperation with the Carnegie Institute of Technology.

Optimum Conditions for Music in Rooms. F. R. WATSON. (*Science*, Aug. 27, 1926.)—"Musicians claim that rooms are usually ruined for music if they are adjusted by sound-absorbing materials to give 'perfect' acoustics. On the other hand, rooms left reverberant so that musicians find it 'easy' to play and to sing are quite objectionable for satisfactory listening." Mr. Watson set out to make experiments to resolve this seeming contradiction. In a musical performance there are usually two groups of people to be considered, the players and the audience. Accordingly he studied the effect upon both of these when a room with so little reverberation as to appear "dead" to the players was progressively stripped of its sound-absorbing material. The players found it hard to play in the room at first, but playing grew easier as the reverberation increased. On the contrary, the listeners felt that conditions of hearing became worse and worse with the increase of reverberation. The same general results were attained in other rooms with a range of volume from 12,000 to 200,000 cu. ft.

An experiment in a small studio revealed how to please audience and performers in the same room. At first the studio was made "perfect" for listening by the adjustment of absorbent material. The members of a string quartette found the conditions objectionable for playing. Some of the absorbent material was shifted from their vicinity to the other end of the room. Both players and audience declared that the music sounded better. The best results in the judgment of both groups was had when all the sound-absorbent material was removed from the neighborhood of the quartette to the other end of the room. "Musicians find it hard to play if surrounded by sound-absorbing materials, and the resultant music is not acceptable for listeners, so that the effect is unsatisfactory to all. By shifting the sound absorbents to one end of the room, a reverberant space is left for the easy generation of music—the musicians find free expression for the finer details of the compositions and the listeners are doubly fortunate in having good music to listen to and in having a deadened surrounding which makes listening enjoyable." Throughout the room the duration of reverberation was the same, but the sound was louder near the musicians than at the deadened end. The preceding conclusions furnish an explanation of musical conditions observed in a large auditorium. Perfect conditions were predicted provided 6700 people attended and thus furnished absorbing material. For some reason when Paderewski played, the audience lacked 1200 of this number. The vacant seats were largely near the platform and the pianist, the hall was "wonderful in its response," while the auditors, perforce located where the absorbing material was, likewise praised the hearing properties of the auditorium.

The outcome of this series of experiments has manifold applications to direct listening and also to broadcasting. G. F. S.

THE FRANKLIN INSTITUTE.

(Proceedings of the Stated Meeting held Wednesday, October 20, 1926.)

HALL OF THE FRANKLIN INSTITUTE,
PHILADELPHIA, October 20, 1926.

THE regular monthly meeting was called to order at eight-sixteen o'clock by the President of the Institute, Dr. Wm. C. L. Eglin.

The attendance was such that every chair was taken, the aisles were filled, and all standing room was occupied. Many persons desirous of attending had to be turned away.

The President announced that the minutes of the preceding meeting had been published in the JOURNAL for June and that unless there were some correction of those minutes, they would be approved as printed. No correction being offered, the minutes were declared approved as printed.

The Secretary announced that since the last meeting, twenty-seven persons had been elected to membership in the Institute, and announced with regret the death of six members during that interval. One of these six was Mr. Lawrence T. Paul, a long time member of the Board of Managers.

The Secretary called to the attention of the members of the Institute and their friends the exhibit of The Franklin Institute in the Palace of Education at the Sesqui-Centennial Exposition, and urged them to visit this exhibit.

He made a statement concerning Management Week which will be celebrated throughout the United States in the week October twenty-fifth to October thirtieth, and stated that meetings would be held in the Hall of the Institute for the first four nights of that week, to which meetings all interested persons are invited.

The Secretary also made an announcement concerning the presentation to the Institute of a portrait of Mr. Coleman Sellers, which is to be donated by Mr. Sellers' daughter, Mrs. S. W. Colton, Jr. The formal presentation will be made on the afternoon of Wednesday, November tenth, to which all members of the Institute are cordially invited. Formal notice will be sent out at a later time.

Presentation was then made of a Longstreth Medal and two Potts Medals, which were awarded last spring but which had not been formally presented.

The President recognized Mr. C. E. Bonine, who in presenting Mr. Alonzo G. Kinyon said: "Mr. President, I have the honor to present, upon recommendation of the Committee on Science and the Arts of The Franklin Institute, Mr. Alonzo G. Kinyon, of Fullerton, Penna., as the recipient of the Edward Longstreth Medal, in consideration of new and important improvements in the art of conveying pulverized materials. I present Mr. Kinyon."

After presentation of the Medal by President Eglin, Mr. Kinyon expressed his appreciation of, and gratitude for, the honor which had been done him.

The President then recognized Prof. H. J. Creighton, who, in presenting

Mr. H. W. Matheson, said: "Mr. President, I have the honor to present, upon recommendation of the Committee on Science and the Arts of The Franklin Institute, Mr. Howard W. Matheson, of the Canadian Electro Products Company of Montreal, as the recipient of the Howard N. Potts Medal, in consideration of the inventive skill and ingenuity, and the application of scientific information, displayed in the development of a successful commercial process for the oxidation of acetylene to acetaldehyde and acetic acid from previously known chemical reactions. I present Mr. Matheson."

After the presentation of the Medal by President Eglin, Mr. Matheson expressed his appreciation of the honor done him and his satisfaction in receiving it.

The Secretary of the Institute read a telegram just received from the Montreal Section of the Society of Chemical Industry, which follows:

"At a meeting of the Montreal Section of the Society of Chemical Industry, held October eighteenth, the following resolution was passed: That the Montreal Section of the Society of Chemical Industry sends greetings to The Franklin Institute of the State of Pennsylvania for the Promotion of the Mechanic Arts, with an expression of appreciation of the honor done to its member and former Chairman, Mr. Howard W. Matheson, by the said Institute in awarding him the Howard N. Potts Medal in consideration of the inventive skill and ingenuity displayed in developing a successful commercial process for the manufacture of acetaldehyde and acetic acid from acetylene, and that the Section offer to Mr. Matheson its hearty congratulation upon this well-deserved recognition of his notable achievement by so distinguished a scientific institution. J. R. MacAuley, Secretary."

The President then recognized Dean Frederick Palmer, who in presenting Dr. W. D. Coolidge said: "Mr. President, I have the honor to present, upon recommendation of the Committee on Science and the Arts of The Franklin Institute, Dr. William D. Coolidge, of the General Electric Company, of Schenectady, N. Y., as the recipient of a Howard N. Potts Medal, in consideration of the originality and ingenuity shown in the development of a vacuum tube that has simplified and revolutionized the production of X-rays. I present Doctor Coolidge."

After the presentation of the Medal, Doctor Coolidge thanked the Institute in felicitous terms for the honor which he felt had been done to him.

The President of the Institute presented Doctor Coolidge as the speaker of the evening, who then talked upon "The Production of High-voltage Cathode Rays Outside of the Generating Tube."

Doctor Coolidge's paper presented many striking and novel features and matters of commanding interest. The paper was followed by a protracted discussion which was participated in by a number of the leading physicists and investigators of the United States.

The meeting adjourned at nine-thirty-five P.M., with a rising vote of hearty appreciation for Doctor Coolidge's paper.

The meeting was followed by an informal discussion which continued until well after ten o'clock.

HOWARD MCCLENAHAN,
Secretary.

RESOLUTIONS REGARDING THE DEATH OF MR. LAWRENCE T. PAUL, ADOPTED BY THE BOARD OF MANAGERS.

At a meeting of the Board of Managers of The Franklin Institute, held October 13, 1926, the following Resolutions were adopted:

Resolved: That the Board of Managers has learned with extreme regret and heartfelt sympathy of the death of Mr. Lawrence T. Paul, a long time member of this Board, and an interested and helpful member of The Franklin Institute.

Resolved: That the Secretary of the Institute be requested to express in proper terms to the family of Mr. Paul, the sympathy which this Board feels and the appreciation of the loss which it has suffered in the death of Mr. Paul.

In accordance with these actions, the Secretary has sent to the Family of Mr. Paul a proper expression of the sorrow and sympathy of the Board of Managers.

COMMITTEE ON SCIENCE AND THE ARTS.

(Abstract of Proceedings of Stated Meeting held Wednesday, October 6, 1926.)

HALL OF THE COMMITTEE,
PHILADELPHIA, October 6, 1926.

MR. JAMES S. ROGERS *in the Chair.*

The following report was presented for final action:

No. 2854: Shockless Jarring Machine.

This machine was devised for the purpose of removing the jar communicated to a building in which machine molding is being carried on.

In machine molding the flask is placed upon the table of the machine while the pattern is placed in position and the sand filled in around it. The table carrying the flask is then raised a short distance above the anvil and dropped upon it to pack the sand around the pattern. This is repeated until the sand is thoroughly packed.

The striking of the table with its load upon the anvil produces a series of shocks that are communicated to the anvil support and set up troublesome vibrations in the building. To overcome this, the anvil of this device is made to rise, as the table drops, with such velocity as to counteract the force of the blow. As a result, while the sand is jarred in place around the pattern, there is no shock communicated to the building.

The following reports were presented for first reading:

No. 2809: Dry Coal Preparation.

No. 2852: Work of Dr. D. C. Miller in Sound.

GEO. A. HOADLEY,
Secretary to Committee.

MEMBERSHIP NOTES.

ELECTIONS TO MEMBERSHIP.

(Stated Meeting, Board of Managers, October 13, 1926.)

RESIDENT.

MR. WILLIAM FINDLAY DOWNS, Vice-president, Day and Zimmermann, Inc., 1600 Walnut Street, Philadelphia, Penna.

MR. WILLIAM A. DOUGLASS, Research Chemist, Jackson Laboratory, Wilmington, Del. For Mailing: 29 Ziegler Tract, Penns Grove, N. J.

NON-RESIDENT.

MR. JOHN C. KUBALE, Electrical Engineer, General Electric Company, Schenectady, N. Y. For Mailing: 101 Glenwood Boulevard, Schenectady, N. Y.

MR. LLOYD LOGAN, Research Associate, Gas Engineering, Johns Hopkins University, Baltimore, Md. For Mailing: Room 29, Mechanical and Electrical Building, Johns Hopkins University, Baltimore, Md.

STUDENT.

MR. JULIUS D. HYMAN, Student, 2230 North Park Avenue, Philadelphia, Penna.

CHANGES OF ADDRESS.

MR. BENJAMIN F. ADAMS, 948 Buchanan Avenue, Lancaster, Penna.

DR. ROBERT J. ANDERSON, 2448 Beekman Street, Cincinnati, Ohio.

MR. GEORGE W. BIRCH, JR., 8921 West Chester Pike, Kirklyn, Penna.

MR. J. H. BURROUGHS, 300 Bullitt Building, Philadelphia, Penna.

MR. MORRIS L. COOKE, St. George's Road, Mt. Airy P. O., Philadelphia, Penna.

MR. KARL K. DARROW, 230 West Tenth Street, New York City, N. Y.

MR. J. E. EGLESON, 39 South Munn Avenue, East Orange, N. J.

MR. R. B. ERICKSON, 1726 Roslyn Street, Philadelphia, Penna.

MR. WILLIAM G. ELLIS, 1811 Washington Street, Wilmington, Del.

MR. GEORGE R. HALL, 718 Widener Building, Philadelphia, Penna.

MR. EDWARD HEITMAN, Lee Crest, Second and Blaine, Detroit, Mich.

MR. GEORGE HOFFSTETTER, 1013 Filbert Street, Philadelphia, Penna.

DR. ENOCH KARRER, 16207 Nelaview Avenue, East Cleveland, Ohio.

MR. CHARLES F. KELLERS, 947 Maple Avenue, Schenectady, N. Y.

MR. W. M. C. KIMBER, Ojai, Venture County, Calif.

PROF. CHARLES E. LUCKE, 845 West End Avenue, New York City, N. Y.

NELSON B. MAYER, ESQ., Hotel Gladstone, 114 East Fifty-second Street, New York City, N. Y.

DR. WALTER M. MITCHELL, Assistant Sales Manager, Development Division, Central Alloy Steel Corporation, Massillon, Ohio.

MR. H. B. OATLEY, 33 Arleigh Road, Kensington, Great Neck, L. I., N. Y.

DR. SAMUEL E. POND, School of Medicine, University of Pennsylvania, Philadelphia, Penna.

MR. A. M. RANDOLPH, P. O. Box 489, Warrenton, Va.

MR. RICHARD G. SAGEBEER, Swarthmore Preparatory School, P. O. Box 34, Swarthmore, Penna.
MR. CHARLES E. SARGENT, 1433 Linden Street, Allentown, Penna.
DR. MAXIMILIAN TOCH, 443 Fourth Avenue, New York City, N. Y.
MR. JOHN C. TRAUTWINE, 3RD, Box 26, Wallingford, Penna.
DR. ROBERT H. WILHELM, 1 Cleveland Avenue, Narberth, Penna.
REAR-ADMIRAL WILLIAM S. SIMS, 73 Catherine Street, Newport, R. I.

NECROLOGY.

Mr. Frederick A. Canfield, Dover, N. J.
Lawrence T. Paul, Esq., Philadelphia, Penna.

MEMBERSHIP ACTIVITIES.

Announcement is made of the formation of Robert J. Anderson, Inc., to operate as a commercial testing laboratory, specializing in metals and alloys.

The new laboratory in Cincinnati, Ohio, is equipped for chemical analysis, mechanical testing, metallography, heat treatment, and radiography.

The laboratory staff comprises a corps of qualified chemists and metallurgists under direction of Dr. Robert J. Anderson, metallurgical engineer, expert on aluminum and author of "Metallurgy of Aluminum and Aluminum Alloys."

LIBRARY NOTES.

RECENT ADDITIONS.

DOYLE, AIDA M., Editor.—Digest of Patents Relating to Coal-tar Dyes and Allied Compounds: United States Patents Issued Prior to January 1, 1924. 1926.
HOWE, HARRISON E.—Chemistry in the World's Work. 1926.
KLUZ, THOMAS.—Calcul Graphique des Poutres Continues à Section Constante. 1926.
MARTIN, GEOFFREY.—The Modern Soap and Detergent Industry, Including Glycerol Manufacture. Vol. 3, The Manufacture of Glycerol. 1926.
MAYERHOFER, E., and PIRQUET, C.—Lexikon der Ernährungskunde. 1923.
Moss, HERBERT.—The Enlarged Heat Drop Tables. H. P. Gauge Pressures. L. P. Absolute Pressures. 1925.
Philadelphia City Directory, 1926.
SCOTT, WILFRED W.—Inorganic Quantitative Chemical Analysis. 1926.
Who's Who in America. Vol. 14, 1926–1927. 1926.

THE FRANKLIN INSTITUTE AND STANDPATISM.

THE following clipping, which is taken from the *Philadelphia Evening Bulletin* of September 15, 1926, should be of interest to members of The Franklin Institute for two reasons: It indicates that from its earliest days, the Institute was progressive and successful; it shows also that "standpatism" and ultra-conservatism were not unknown even among the fathers of the Nation:

ONE HUNDRED YEARS AGO.

(From the *Philadelphia Gazette* of September 15, 1826.)

"The High School of the Franklin Institute. We understand that, in consequence of the great number of applications for admission to the institution, beyond what can be received with the present arrangement, it is intended to open a new department as soon as the necessary accommodations can be prepared."—*National Gazette.*

We sincerely hope that before a new department is opened time will be allowed to test the excellency of the system that has been adopted. Three hundred and four boys are quite enough to make an experiment upon and, if the experiment should chance to fail, what compensation can the proprietors of this new establishment offer to society for the evil done in breaking up the private schools.

BOOK REVIEWS.

RAIN MAKING AND OTHER WEATHER VAGARIES. By W. J. Humphreys, United States Weather Bureau. x–157 pages, small 8vo. Baltimore, The Williams and Wilkins Company, 1926. Price, $2.50.

"Rainy, rainy shower;
Go away and come to-morrow."

Notwithstanding the lameness of the rime and the almost universal failure of the exorcism, children are probably still uttering the couplet when annoyed by the "uncertain glory of an April day." For centuries mankind relied for weather prognostications upon folk-lore tempered with inferences from experience, but the weather depends upon conditions over a wide area, and, until a system of prompt transmission of intelligence was invented, little satisfaction could be obtained. Mankind is never content, and now-a-days, when weather predictions are fairly accurate for a period of a day or more, a desire is expressed for longer ranges. This desire indeed has been utilized for a long while by the makers of almanacs and to each month has been assigned a paragraph which many have consulted and still consult with abiding faith. The general principle is fairly simple, namely, in predictions for the northern hemisphere not to put thunderstorms in January or snow in July. Our fellow creatures at the antipodes, however, have a reverse situation. They wear overcoats in July and go picknicking on New Year's day. It is interesting indeed to note in their botanies, for instance, wild plants flowering from "November to February."

In the book in hand, Doctor Humphreys has collected a large amount of information concerning the unscientific folk-lore views on weather and its changes. He takes occasion, as all scientific meteorologists do, to deprecate the common belief in an "equinoctial storm." The view has, indeed, no basis in careful observation, yet in common experience severe storms do often occur about the third week of March and September. The persistence of the belief is due, as in most other cases, to the fact that an incident according with the belief produces a deeper impression than a failure of occurrence. A similar view, which Doctor Humphreys also ranks as a vagary, is the weekly period

of bad weather. This seems to have no basis when statistical investigation is made, yet persons who have over a term of several months weekly appointments are often inclined to believe that there is something of lunar influence in the determination of the weather.

Some years ago the United States Weather Bureau published a large collection of weather-lore, obtained by careful investigation among the people of this country. Farmers and sailors are among the most zealous collectors and utilizers of such lore. They are the classes with whom the vagaries of the weather are most serious. Excessive rains and long drouths mean much to the former. Storms and calms much to the latter, although for many years past the application of steam and other sources of power have rendered "doldrums" of no moment. The writer of Ecclesiastes, whom Dr. Morris Jastrow called "A Gentle Cynic," says: "He that observeth the wind shall not sow and he that regardeth the clouds shall not reap," but he was probably a white collar, armchair man who had not labored in field or garden.

HENRY LEFFMANN.

WASSERKRAFT-JAHRBUCH, 1925–1926. Herausgeber: Oberbaudirektor K. Dantscher, Ord. Professor, München; Ingenieur Carl Reindl, München. 386 pages, illustrations, plates, tables, 8vo. Munich, Richard Pflaum, Druckerei- und Verlags-A.G., 1926. Price, bound, 16 marks.

The second edition of this useful volume, which has just come from the press, contains information and data on every phase of the water-power problem. Nine engineers contribute papers on the present condition of water-power plants in the leading European countries. The applications of hydraulic power to chemical and metallurgical purposes is the subject of one contribution, while another is devoted entirely to water power and aluminum. There is a timely article on the aerial photograph and its importance in hydraulic work; the accompanying illustrations, twelve in number, include the camera and accessory apparatus and several views taken in aerial flights. The fourth section comprises articles on recent developments in turbines and other hydraulic machinery and new power-plant installations and a supplementary section includes general hydraulic data and tables, a note on nitrogen fixation and other useful information.

R.

ENLARGED MOLLIER OR H-ϕ DIAGRAM FOR SATURATED AND SUPERHEATED STEAM. Plotted by Prof. H. L. Callendar, F.R.S., from his Enlarged Steam Tables. Published by Edward Arnold and Co., London, for the British Electrical and Allied Industries Research Association, 1926. Price, 4 s. net.

Diagrams of many forms representing the variables of the properties of steam have become of proved utility in recent times for the expeditious solution of thermodynamic problems. Among these the form in which temperature and entropy are chosen as coördinates has received wide application. In this form the quantity of heat is represented by an area which can only be read directly by the addition of lines of constant heat.

The present diagram is a rendition of the well-known Mollier diagram

based on the author's steam tables in which the coördinates are entropy and quantity of heat. Here the quantity of heat is directly determined by simple scale-measurement. Professor Callendar points out in his treatise on the properties of steam the advantages and defects of this diagram. The chief difficulty, he says, is that the lines of constant volume cannot be inserted without risk of confusion with the lines of constant pressure. He has, however, overcome this difficulty by the judicious use of red ink. The lines of constant volume are in red while the pressure lines are in black, and their possible confusion is thereby much mitigated. Values of entropy are from 1.36 to 2.02 to a scale of 1 mm. = 0.001 ϕ; the scale of total heat is, 1 mm. = 1 B.T.U. per lb. from 700 to 1500, which makes the diagram 66 × 80 cm.

The diagram, which is plotted on cross-section paper of 2-mm. spacing, is an unusually fine piece of draftsmanship, there being not a break or flaw visible in any of the lines. The notation and figures are equally well executed. The accurate registry of the lines of the diagram with the cross-section lattice is a highly creditable piece of presswork. The title is the only feature not on a footing with the draftsmanship. It seems somewhat too large and would have better appearance if set up in printers' type.

LUCIEN E. PICOLET.

THE ELEMENTS OF MOTOR VEHICLE DESIGN. A text-book for students and draftsmen. By C. T. B. Donkin, A.C.G.I., Assoc.M.Inst.C.E., Late lecturer in motor car engineering at the Borough Polytechnic Institute. viii–277 pages, 8vo, cloth. New York, Oxford University Press, American Branch, 1926. Price, $4.25.

Something like a standardization of form and general plan of mechanical equipment has come about in the motor car industry and these vehicles now conform to certain well-defined types which have been evolved during the extraordinarily rapid growth of that industry. In matters of structure and mechanism there is an abundance of precedent and the design of the operative elements and the problem before the designer of a given type of car is rather one of machine design of parts of elements whose arrangement and form are prescribed within comparatively narrow limits.

The "Elements" is primarily intended, so the author states, for designers, draftsmen and students. In scope, it deals with mechanical features only, without reference to the body structure; it is a text-book on the design of the "chassis" and its mechanical equipment. The illustrations which explain the text are not copies of the drawings of any particular manufacturer, but are based on current practice in its simplest form, the object being to set forth typical methods rather than specified designs which may vary with particular requirements.

The first five chapters relate to fundamental data, materials of construction, thermodynamics of the Otto cycle, tractive effort and power. These are all, and especially thermodynamics, amply developed and fully illustrated by numerical examples. The succeeding chapters are devoted to the details of the system. A full and rational account is given of the determination of tangential effort and design of the fly-wheel, and is an excellent presentation

of this interesting problem in dynamics. As before, the author is generous with numerical examples. This valuable feature, it may be noted, is applied throughout the work. Valve timing and cam profiles come next with an analysis of cam action and methods of laying-out cam profiles. Due consideration is given the relation of cam profile and spring to maintain contact between cam and tappet.

Carburation and ignition are treated somewhat briefly, but since both of these are highly specialized features, it seems proper to restrict their discussion, as the author has done, to an account of the principles of their action and functioning. There is no mention, however, of the combined electric starting, lighting and ignition system now universally used in passenger cars. A general description and reference to a source of detail information on such equipment would be useful and appropriate. The author is indeed rather sparing of bibliographical references, a matter which is receiving constantly increasing attention on the part of writers of text-books. Clutches are represented by a chapter on the principles and construction of cone, and single and multiple-disc clutches. The chapters on gear boxes, propeller shafts, axles, wheels, steering gear, brakes, frames, springs, radiators and pumps are presented in equally satisfactory form and amplitude. Especial mention may be made of the chapter on the steering gear, which includes some original diagrams for the determination of angles in the steering connections. A suitable number of problems for students' use is given with each chapter.

The work is an excellent reference manual for the designer who may have occasion to refresh his memory on rational methods of design. The subject-matter is also very well arranged for text-book purposes.

LUCIEN E. PICOLET.

COLLOID AND CAPILLARY CHEMISTRY. By Herbert Freundlich, Ph.D., Professor at the Kaiser Wilhelm Institute for Physical Chemistry, Berlin. Translated from the third German edition by H. Stafford Hatfield, B.Sc., Ph.D. xv–883 pages, 157 diagrams and 7 plates, 8vo. New York, E. P. Dutton and Company. Price, $14.

Freundlich has been a pioneer in the field of capillary chemistry, the first edition of his work on that subject having appeared in 1909. It was soon out of print but the information it contained was rapidly assimilated by physical chemists. The translation now offered to readers of English is from the third German edition, for which the text has been entirely rewritten. Many changes in the aspects of science as well as in world affairs at large have occurred in the interval between the first edition and the present. Physical chemistry has continued its onward march with Tarquin strides, developing both the theoretical and practical phases. Mostly we hear of colloids; in the present work the special phase of capillary chemistry is presented, as well as the nature and properties of colloids.

There is little to be said in detailed criticism. The names of the author and translator are sufficient to assure us that the data given are fully up to the present knowledge and have been properly selected and arranged. Largely illustrated by diagrams and tables, the full details of the phenomena are set forth. It has fallen to the lot of the present reviewer to discuss in the past

dozen years a large number of books of the type of this. It is painfully apparent to those who are pleased to call themselves "chemists" that their science is being crowded to the wall by physics. Physicists, whether in sympathy or in triumph, are still linking the terms, though in the course of a half century the order has changed. In the days of Graham, Faraday, Dumas and Hofmann "chemical physics" was a minor, though usual, feature of our text-books. "Physical chemistry" is now the phrase. There has now come the time when colloid and capillary phenomena should be classified as "physics" alone. The experimental data and the theoretical considerations in a work such as that under review are physical, not chemical, as far as a definite distinction can be made. We should have books on "colloidal and capillary physics." It is true that in these works, chemical substances are mentioned extensively, but in almost all cases it is with regard to physical properties. It is also true that no absolutely strict definition can be given in any department of human knowledge or experience. Every one admits that a cat is an animal and a rose is a plant, but in dealing with slime-molds or even with enzymes, biologists will not all be in accord. Modern authorities do indeed, in many cases, deprecate the attempt to distinguish between "chemical" and "physical" change, but in the practical work of the laboratory the chemist sees a great difference between the magnetization of steel and its solution in acid. The distinction in this case is easily made, but the phenomenon of the latent image on the photographic plate is still a puzzle, and workers in that field are not likely to be unanimous in classifying the action, especially as the details of it are not fully known. Perhaps after all, colloid phenomena have much to do with the action of light, but it is now well known that after exposure the silver halide may be removed by a fixing agent and the picture subsequently obtained in full detail. Possibly the minute amount of halogen which escapes under the influence of light is taken up by the gelatin or other organic medium. If such is the case, a true chemical action has occurred. The inherent difficulties of classification and of obtaining definitions that are at once comprehensive and not overlapping, should not deter us from making attempts. We must not stand, like Horace's rustic, waiting for the stream to run by. Some arbitrary judgment is needed, but the fact that such judgment has been necessary must not be overlooked. The tentative character of all our knowledge must be constantly before us.

This discussion has led away from a specific consideration of Doctor Freundlich's book, but it needs no encomiums from reviewers. It is "*primus inter pares.*" None but itself can be its parallel. It is hardly necessary to add that the literature has been thoroughly sifted and every important item of progress utilized, together with the author's wide and skilful experimental work. German scientists have always been commendable for their cosmopolitan methods, a trait, indeed, which extends to all phases of human action. The pursuit of knowledge for the sake of knowledge has been an especial feature of modern Germany. It cannot be said that other great nations have not been patrons of such work, but it seems that in the last fifty years Germany has been very strikingly the home of the coöperation between theory and practice.

The book deals with the abstruse as well as the elementary phases of the

subject, the German text has been excellently translated and we may be sure that it represents in all parts the author's views. The sheets printed in Great Britain show the black ink impression usual in British books, making the reading more easy than the sepia tones often used in American printing.

The reviewer proposes to make the beginning of a crusade for the transfer of colloidal and capillary phenomena to the domain of physics. Perhaps in a mixture of Cato's language and his own, he can say: "*Et ceterum censeo nomen Colloidal chemistry esse delandam.*"

HENRY LEFFMANN.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS. Report 239, Power Output and Air Requirements of a Two-stroke Cycle Engine for Aeronautical Use. By C. R. Paton and Carlton Kemper. 11 pages, illustrations, quarto. Washington, Government Printing Office, 1926. Price, ten cents.

The investigation herein reported was undertaken by the Committee at its research laboratory, Langley Field, Va., in order to determine the pressure and amount of air necessary for satisfactory high-speed two-stroke cycle operation and thus permit the power requirements of the air pump or blower to be determined. Assembly and development of the apparatus and preliminary work in connection with the fuel-injection system were done under the direction of Mr. Robertson Matthews.

The object of this investigation was to determine the pressure and amount of air necessary for satisfactory scavenging and operation of a high-speed, two-stroke cycle engine for aeronautical use, a 5 by 7-inch single-cylinder Liberty test engine being adapted for the purpose. The fuel and scavenging system consisted of a fuel-injection pump and injection valve, used in conjunction with a separately driven Roots type blower. Tests were conducted at speeds of 1000, 1200, and 1300 revolutions per minute, with air-supply pressures from 2 to 6 lbs./sq. in. gauge, and results show that 53 brake horsepower could be developed at 1300 revolutions per minute with a scavenging air-pressure of 5.5 lbs./sq. in., a specific air consumption 9 lbs./b. hp./hr., and a specific fuel consumption of 0.61 lb./b. hp./hr. Under these conditions 3 horsepower was required to supply the air, resulting in a net power output of 50 brake horsepower. A minimum specific air consumption of 8.4 lbs./b. hp. was obtained at this speed with an air-supply pressure of approximately 3.5 lbs./sq. in. when developing 41 brake horsepower. Chattering of cam-operated exhaust valves prevented higher speeds.

Based on power output and air requirement here obtained the two-stroke cycle engine would seem to be favorable for aeronautical use. No attempts were made to secure satisfactory operation at idling speeds.

REPORT 242, Characteristics of a Twin-float Seaplane during Take-off. By John W. Crowley, Jr., and K. M. Ronan. 16 pages, illustrations, quarto. Washington, Government Printing Office, 1926. Price, ten cents.

At the request of the Bureau of Aeronautics, Navy Department, an investigation has been made, by the Langley Memorial Aeronautical Laboratory of the Committee, of the planning and get-away characteristics of three representative types of seaplanes, namely, single float, boat, and twin float. The experi-

ments carried out on the single float (Reference 1) and boat (Reference 2) types have been reported on previously. This report covers the investigation conducted on the twin-float seaplane, the DT-2, and includes, as an appendix, a brief summary of the results obtained on all three tests.

The fundamental take-off characteristics of the DT-2 seaplane (twin float) are similar to those of the N-9H (single float) and the F-5L (boat type). At low water speeds, 20 to 25 M.P.H., the seaplane trims by the stern and has a high resistance. Above these speeds the longitudinal control becomes increasingly effective until, with a gross load of 6000 pounds, it is possible to get away at angles of attack of 8 to 14 degrees with corresponding speeds of 56 to 46 M.P.H. It was further determined that an increase in the load caused little if any change in the water speed at which the maximum angle and resistance occurred, but that it did produce an increase in the maximum angle.

THE MOSQUITOES OF THE LOWER FRASER VALLEY, BRITISH COLUMBIA, AND THEIR CONTROL. By Eric Hearle, M.Sc., Assistant Entomologist in charge of mosquito investigations, Entomological Branch, Department of Agriculture, Ottawa. National Research Council Report No. 17. 94 pages, illustrations, plates, 8vo. Ottawa, King's Printer, 1926.

Mosquitoes have long been recognized as a pest in many parts of the world, but only in the last thirty years has it been definitely known that they were also responsible for the transmission of disease. Yellow fever has been almost completely eradicated and malaria has been brought under control through the adoption of destructive and protective measures in dealing with the mosquito pest. In northern climates they do not transmit disease to any large extent.

Mosquitoes were abundant in the Lower Fraser Valley of British Columbia when the first settlers entered that district, and even yet they are so numerous in certain years as to cause a considerable economic loss. They are at the height of their activity during the berry-picking season, and sometimes seriously interfere with the gathering of that crop. Livestock suffer keenly from mosquitoes, losing much in weight, and the yield of milk and butter is materially reduced. At times mosquitoes are so numerous as to interfere with lumbering and building operations.

The investigation described in the volume was carried out by Mr. Eric Hearle, M.Sc., who began work as the holder of a scholarship under the National Research Council and completed it while in the employ of the Entomological Branch of the Dominion Department of Agriculture. He secured in the Fraser Valley specimens of twenty-four species of mosquitoes, and studied in detail the two species constituting the pest.

The author expresses the opinion that mosquitoes may be greatly reduced in numbers in this district by the construction of dykes to prevent the flooding of cottonwood swamps and meadow areas, in which the two worst species breed. Reclamation and clearing have already greatly improved the situation. Oiling might be used effectively in small flood areas. It is strongly recommended that the municipalities concerned should coöperate in an effort to mitigate this nuisance.

CHEMICAL ENGINEERING CATALOG. 1926 (eleventh annual) edition. 1175 pages, illustrations, quarto. New York, The Chemical Catalog Company, Inc., 1926. Price, $10; leasing fee, $2.

The new edition of this useful volume has just been published and all the excellent features of the previous editions have been continued. The work is divided into four sections: The Classified Index of Equipment and Materials; The Equipment Section; The Chemicals and Materials Section; and The Technical Books Section, each being supplied with the necessary subject and name index. The Book Section contains 2000 titles of works on all branches of chemistry with indication of size, date of publication and cost. The Catalog is published under the supervision of a special committee appointed by the American Institute of Chemical Engineers, the American Chemical Society and the Society of Chemical Industry.

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Wasserkraft Jahrbuch, 1925–1926. Herausgeber: Oberbaudirektor K. Dantscher, Ord. Professor, München, Ingenieur Carl Reindl, München. 386 pages, illustrations, plates, 8vo. München, Richard Pflaum, Druckerei- und Verlags-A.G., 1926. Price, 16 marks.

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National Advisory Committee for Aeronautics. Bibliography of Aero-

nautics, 1923, by Paul Brockett. 144 pages, 8vo. Technical Notes, No. 246. Test of a Model Propeller with Symmetrical Blade Sections, by E. P. Lesley. 11 pages, illustrations, quarto. Washington, Committee, 1926.

Reading with a Purpose. The Physical Sciences, by Edwin E. Slosson. 30 pages, 12mo. Chicago, American Library Association, 1926.

Clearing the Way for the Comforts of Life. The American home gains beauty and convenience through a century of progress on the "roads of iron." 16 pages, illustrations, 8vo. New York, Ingersoll-Rand Company, 1926.

The Employer; His Responsibilities. An address delivered before the Congress of American Industry, by Charles Piez, Chairman, Link-Belt Company; President, Illinois Manufacturers' Association, Philadelphia, Penna., September 22, 1926. 13 pages, 8vo.

Bureau of Standards: Handbook No. 9, Safety Rules for Radio Installations. 24 pages, 12mo. Price, ten cents. Scientific Papers, No. 531, A Principle Governing the Distribution of Current in Systems of Linear Conditions, by F. Wenner. 18 pages, illustrations, quarto. Price, ten cents. Technologic Papers, No. 320, A Fabric Tension Meter for Use on Aircraft, by L. B. Tuckerman, G. H. Keulegan, and H. N. Eaton. 16 pages, illustrations, plates, 8vo. Price, ten cents. Washington, Government Printing Office, 1926.

Bureau of Standards Anniversary.—A celebration of the twenty-fifth anniversary of the Bureau of Standards of the Department of Commerce is just announced. On Saturday, December 4th next, the Bureau will keep Open House and a banquet will be given at which the many friends of the Bureau will meet the staff and reminiscences will be exchanged, the achievements of the quarter century will be reviewed, and the present and future work will be discussed. A group of distinguished guests will attend. The event is of interest to the world of science and as well to the industrial experts who have worked so closely in coöperation with the Bureau and in turn made application of its discoveries and developments in perfecting the measured control of processes. The opportunity to inspect the experimental research facilities of the Bureau will be welcomed by its many friends.

CURRENT TOPICS.

THE PROGRESS OF THE ENGLISH SYSTEM OF WEIGHTS AND MEASURES.*

ITS PRACTICAL VALUE AS A BASIS OF MANUFACTURE AND COMMERCE.

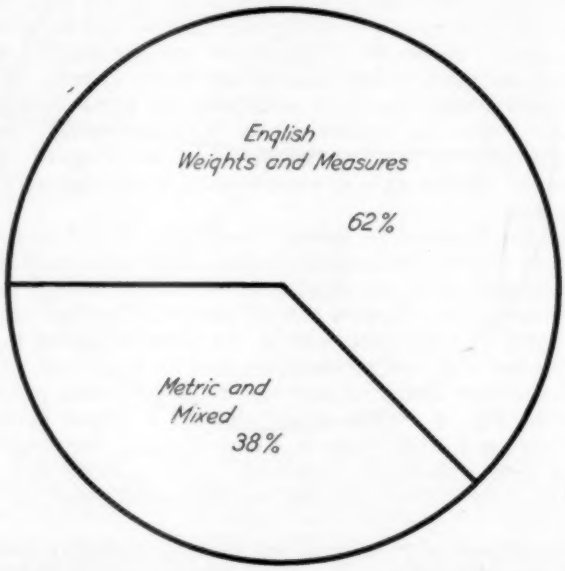
BY

LUTHER D. BURLINGAME.

Brown and Sharpe Manufacturing Company.

THE use of the English system of weights and measures is, like the English language, extending year by year more widely to every distant corner of the world. When Clemenceau was challenged in

FIG. 1.



the French Chamber of Deputies for sanctioning the use of English as the official language of the Peace Conference, he exclaimed: "It is not my fault that two-thirds of the civilized world speaks the English language"; so likewise the system of English weights and measures, inherited from the mother country and an integral part of our language, is following that language wherever it goes. In some of its uses this system is well nigh universal. Among these may be mentioned the nautical mile, the tonnage of vessels based on cubic

* Communicated by the Author.

foot displacement, the draft of vessels, etc. In other uses it predominates to a great degree, as in the use of screw threads, an estimate being that 80 per cent. of the screw products of the world are made to the U. S. and English systems. In the manufacture of textiles the use of the English system is almost universal. As America produces 83 per cent. of the automobiles of the world, this alone carries our system to the remotest frontiers.

The value of imports and exports constitutes one of the more important items forming a basis for comparison. Fifty-nine per cent. of the imports and 68 per cent. of the exports of the Western Hemisphere are now by the English system. Fig. 1 shows graphically the relative standing of the two systems for combined imports and exports. When it comes to a consideration of the developed resources of the countries of this hemisphere, the present use of the metric system sinks into insignificance. Ninety-five per cent. of the developed water power, 80 per cent. of the railroads, 81 per cent. of the telegraphs, 97 per cent. of the telephones, 99 per cent. of the coal are to the credit of countries using the English system, showing the real "progress" to be the progress of our established system of weights and measures, rather than of the metric system. The wealth of the United States has been multiplied by three during the last twenty years, also the wealth of the British Commonwealths has greatly increased, so that by this standard the English system has shown greater relative gain in recent years when compared with the metric system.

In 1921 the National Industrial Conference Board made a report: "The Metric *Versus* the English System of Weights and Measures," after an extended study in coöperation with a Bi-Partisan Committee, and this investigation showed that of the entire export trade of the world in 1919, 48.2 per cent. was by the countries using the English system, 37.5 per cent. metric countries and 14.3 per cent. other countries where neither metric system nor English system predominated, as shown in Fig. 2. This report showed a larger percentage of exports from the United States to countries using the English system than to all metric countries combined. It is reported that the great basic industry of cotton spinning is, the world over, 95 per cent. on our system.

The importance of preserving our present standards, and the difficulty of changing them, has been compared by Major Earle Buckingham with forcing a new language on a people. He says, "In many ways, a single uniform language for the world would be of advantage. The difficulties to overcome to secure this end have thus far been too great to make any progress. For one thing, innumerable translations would be required to preserve the great mass of valuable literature. Again, the difficulty of forcing upon the mass of people a new tongue has proven insuperable time and time again. Such an attempt would only lead to confusion that would require many generations to overcome. Thus the best language is that which

the mass of people in any community understand and use, regardless of its structure.

"The same is true in regard to systems of measurement. Measurements of one sort or another are the only means of comparison that exist. An arbitrary change in a system of measurement for any people means an abrupt break from the past and confusion that may never be entirely eliminated.

"It is not necessarily a question of the relative merits of the English and metric systems of measurement. The great majority of measurements are not made by scientists. Almost every detail of

FIG. 2.

our daily life involves measurement. All trade and commerce is but a measurement of value against some measurement of quantity, etc. In number, the majority of these measurements are local ones, that is, among the people of given communities. The best system for such measurements is the one most widely used, and therefore best understood in that community. These measurements are not matters of scientific knowledge but are necessary details of the daily life of the individual members of the community. An arbitrary change in the system of measurement thus employed would be a public calamity."

There will always be a conflict between practice and theory so long as theorists attempt to enforce standards which practical men abhor. There is nothing in the metric system comparable in clearness and adaptability to general use to the subdivisions on an ordinary

two-foot rule. Binary subdivisions produce a scale of unqualified legibility, while decimal subdivision becomes more and more difficult to decipher.

Mr. Wilfred Lewis tells of an experience of his son in France during the war in which he found French carpenters were not using metres with subdivisions at all, they had what appeared to him to be an English two-foot rule graduated in the same way as our rules, thus indicating their preference for a system based on units of convenient size and having binary divisions.

Now that there is a renewed agitation for the compulsory adoption of the metric system in this country, it may be well to note some reasons why it is believed that a change would not be advisable:

Because of the importance of the preservation of our established basic standards.

Because of the value of the unity we now have. One system only in general use.

Because of the advantages of the present system with binary divisions and units capable of more varied divisions as compared with a system based on ten.

Because of the importance of retaining compound units such as bushels per acre; pounds per square inch; tons per square foot; ton-miles; board-feet, etc.

Because of the preponderance of our commerce on the basis of the present system, the advantage of which would be lost if a change were made.

Because of the reference to weights and measures in our literature, general as well as technical, permeated as it is now with our present standards. This includes the importance of having a system of weights and measures accord with the language, as does our present system with its simple single syllable words.

Because of the heavy burden, involving great cost, a change would load on manufacturers and on the people as a whole.

Because of the persistence of old units confusing them with the new and requiring a knowledge of both for many generations after a change has been made.

Because of the more convenient units of our established system suited to common use, there being no units in the metric system according with our inch, foot, pound, etc.

Because when a decimal system is desired for calculation, the present system can be and is conveniently decimalized. For example, for larger measurements 10, 100 or 1000 feet, and in the use by surveyors of 10th and 100th of a foot, while for finer measurements in the machine shops 100ths and 1000ths of an inch are in every-day use.

Because our land surveys and plats would be seriously affected by a change, in fact to such an extent that a change would be practically prohibitive.

Because the workman using measurements would, if required to

change, lose a degree of the skill he had acquired by familiarity with our convenient measures; for example, the two-foot rule and its divisions; the inch and its decimals.

Because the workman would have to invest in a new kit of tools.

Because the tradesman would have to replace his weighing and measuring appliances, for example, every grocer, every postoffice and all gasoline filling stations throughout the country.

The Production of Single Crystals of Metals and Some of Their Properties. H. C. H. CARPENTER. (*Nature*, Aug. 21, 1926.)—Metals and alloys as they ordinarily occur are made up of small crystals varying in number from 100,000 to several million per cu. in. These large numbers come about thus. When the liquid solidifies, crystallization starts from many centres and the crystals growing outward in all directions continue their progress until they meet one another. The physical and mechanical properties of metals and alloys are the properties of these small crystals and are dependent on the conditions at the crystal boundaries as well as upon what holds in the body of the crystals. Within the crystal itself there is a definite arrangement of atoms, so that an atom there is surrounded on all sides by other atoms stationed in some particular way. An atom at the meeting place of two crystals, on the other hand, has on one side the directional alignment of one crystal, and on the second side that of the other. It has been known that, when a metal breaks, it breaks through the body of the crystals and not through the boundaries. Thus until recently it has been difficult to gain much information concerning the forces that act at the boundary apart from those effective in the interior. "The great, and indeed fundamental, interest of the problem of preparing a piece of metal in the form of a single crystal, therefore, is that its solution would enable the properties of the metal crystal to be determined."

There are two methods of getting large single crystals, by growing them from the liquid and by causing many small crystals to coalesce into one. Sometimes large crystals are formed naturally in the process of solidification, as was the Tschernoff crystal of iron 6 in. long, discovered in the riser of an ingot in Sheffield in 1880. The intentional production of large crystals from the molten liquid seems first to have been accomplished by Czochralski in 1918. He withdrew a rod at a particular rate from the liquid. The molten metal solidified in such a way that the resulting wire, .5 mm. in diameter, was all one crystal. With tin, lead and antimony he obtained this result. More recently P. W. Bridgman, at Harvard, has prepared much larger single crystals, using bismuth, antimony, cadmium, tellurium, tin and zinc. He also relies upon the gradual cooling of the molten liquid. Melting was done in a vacuum and careful removal of dirt was a condition of success. He got single crystal rods up to a diameter of 2.2 cm.

In the second process of getting large crystals Sauveur appears to have been the first to note that if a metal be subjected to strain and then heated, unusually large crystals are formed. Furthermore he found that there was a certain stress that produced the largest crystals. This observation has been confirmed by work done in Professor Carpenter's laboratory. He with an assistant examined the changes caused in aluminum by the application of strain followed by application of heat. When a rather small deformation had been brought about, the effect of heating was to remove in large degree the effects of the strain. After a larger deformation, however, the application of heat made crystals increase in size. In doing this they advanced their boundaries, invading their neighbors and imposing upon them their orientation. When still greater deformation had occurred, new crystals of small size came into being at the boundaries upon the raising of the temperature. The second of the stages of deformation is consequently the one to be used in order to get large crystals. In the course of these experiments the motion of the boundary of a crystal was actually photographed.

The experimenters after several months of work succeeded in causing about 1,687,000 crystals of aluminum in the form of a sheet to unite to form a single crystal. First the test-piece was heated for six hours to 550° C. This softened the metal and produced "new equiaxed crystals of so far as possible uniform size, the average diameter being 1/150 inch." The second treatment was the application of a stress of 2.4 tons per sq. in., by which an elongation of 1.6 per cent. was produced. The third and last stage consisted in the raising of the temperature of the piece 25° a day from 450° to 550°. Finally for an hour the temperature was brought to 600° to overcome the independence of recalcitrant crystals. By this series of treatments about one-fourth of the test-pieces used turned into single crystals. "The time required for the single crystal to grow in this way is therefore about 100 hours." Encouraged by their success they went on and produced single crystals in the form of circular cylinders 9 in. long and .564 in. in diameter. They even got single crystals with a volume of 2 cu. in. in which some 7,000,000 little crystals had coalesced to form one. The tenacities of such single crystals varied from 3 to 4 tons per sq. in. and the corresponding elongations from 57 to 85 per cent. When more and more force was applied to pull a crystal apart, instead of the metal drawing down but meanwhile maintaining a circular cross-section as is the case with ordinary wire, in this case, on the contrary, it takes on an elliptical cross-section. "The final result was that the fractured surface of each half of the test-piece was a very acute ellipse or wedge, the metal being grooved in each case."

No success was attained in the endeavor to produce single crystals in the form of square bars. In the case of tungsten and molybdenum single crystals of circular cross-section have been obtained by other

workers merely by drawing them at a certain rate through a die, the temperature being meanwhile regulated.

To study the distortion accompanying the elongation of a single crystal, such a crystal in cylindrical form was taken and machined down into a square bar. On each of the four sides a scratch was drawn parallel to the length of the specimen. At intervals of half an inch other scratches were made at right angles to the longitudinal ones. Observations were made on the bar while it was elongated by steps up to 78 per cent. where it broke. "As the test proceeded the square section of the bar gradually disappeared, and the final result was a parallelepiped of remarkable form. The cross-scratches, although remaining rectilinear, shifted by a definite angle which became markedly acute. When the specimen finally broke, it contained two very acute and two very obtuse angles." Professor Carpenter and his assistant examined the results of elongating a single crystal of aluminum and of subsequently heating it. They found that the crystal can be lengthened by as much as 7 per cent. without the following elevation of temperature destroying it. When the elongation is greater than this amount the crystal when heated breaks up into small crystals. When X-rays were employed to follow the geometrical structure of crystals under treatment, it was found that under certain combinations of elongations with subsequent heating the crystal, while remaining a single crystal, had undergone a change in the arrangement of its atoms. G. F. S.

Reminiscences of the Last British Association Meeting in Oxford, 1894. SIR OLIVER LODGE. (*Discovery*, Aug., 1926.)—When the British Association was only a year old, it held a meeting in Oxford in 1832, and it came again to the university town in 1847 and 1860. Its fourth meeting at Oxford was presided over by Robert Cecil, Marquis of Salisbury. In his presidential address he discussed such subjects as the periodic law, the ether of space and the work of Darwin. He emphasized our ignorance on fundamental questions—a position in which Sir Oliver Lodge concurs, saying: "The boundary of our ignorance shifts from time to time as our knowledge slowly increases; but it is never obliterated, and we are still enshrouded by, if not an impenetrable, an as yet unpenetrated region of mystery."

Professor Ruecker was president of the Physical Section. Hiram S. Maxim opened a discussion on flight. He had devised an arrangement on rails by which passengers actually were lifted in a vehicle a few inches from the ground. On one of these trips Lord Rayleigh, who had developed the mathematical theory of the lifting power of an airplane, was thus raised above the earth, though he was urged "not to risk his valuable life as ballast on so dangerous an expedition, but to send a copy of his works, which would be sufficiently heavy for the purpose." Sir Oliver himself gave a demonstration of Hertzian waves. He laid stress on the importance of the theoretical

work of Maxwell and on the experimental work of Hertz. This tribute to the latter was not relished by Ludwig Boltzmann, who rose and took exception to parts of the address. It seems that the physicists of Germany were not too well acquainted with the fundamental work of Maxwell and that Hertz wrote to Sir Oliver Lodge "referring to the difficulty which he had in getting his results understood by the orthodox professors of his own country; always excepting his quondam chief, von Helmholtz."

By a Branly iron-filing coherer the lecturer showed various properties of electric waves. Signals in the Morse code were received from another room, from which they were sent by a telegraphic key controlling the current in an induction coil that operated a Hertz vibrator. The author's confession is interesting: "I had hopes that by the use of short waves, signalling across considerable distances of space could by this means be accomplished; and the late Lord Rayleigh urged me to take this matter up and develop it. I did not follow his advice, being fully occupied in teaching, and I had not the perceptive faculty shown about the same time by Sir William Crookes, who anticipated that such a method of telegraphy would be or might become of international importance."

At this same Oxford meeting Lord Rayleigh announced to the Chemical Section the discovery of argon. His statement was received with much scepticism. G. F. S.

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